Contribution of AGN Outflows to the Metal Enrichment History of the IGM on Cosmological Scales

Paramita Barai (barai@physics.unlv.edu), **Hugo Martel, Joël Germain**

University of Nevada,
Las Vegas, USA.

Université Laval,
Quebéc City, Canada.

Centre de Recherche en
Astrophysique du Quebec.

Abstract

We investigate the large-scale influence of outflows from Active Galactic Nuclei (AGN) in enriching the InterGalactic Medium (IGM) with metals in a cosmological context. A substantial fraction of AGN are observed to host outflows powered by their central supermassive black holes. The outflows expand and permeate significant volumes of the Universe, having feedback on further evolution of the filled volumes. We implement semi-analytical prescriptions of the propagation of AGN outflows (along with a model of metal enrichment) within a cosmological volume, and perform N-body simulations of large-scale structure formation in a ΛCDM Universe. The AGN outflows carry metals generated by stellar populations within the host galaxy and distribute the metals into the large-scale IGM. We compute the fractional volume of the simulation box filled by the outflows of a cosmological population of AGN over the Hubble time, and analyze the resulting metallicity in the filled volumes. The dependences of the IGM metal-enrichment on other factors (such as, AGN luminosity and IGM overdensity) are studied, and compared with observations.

Introduction

- Outflows are observed in a large fraction of Active Galactic Nuclei (AGN), in a wide variety of forms [2]
- AGN outflows play important roles in the formation and evolution of galaxies, large-scale structures, and the intergalactic medium (IGM)
  - Metal enrichment of the IGM, modifying of the cooling rate of star-forming gas
  - Heat / displace / compress proto-galactic gas affecting further star / galaxy formation

- Goal :

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

➢ Calculate the volume fraction of the Universe filled [4], Metallicity in the filled volumes [1]

Metallicity of IGM

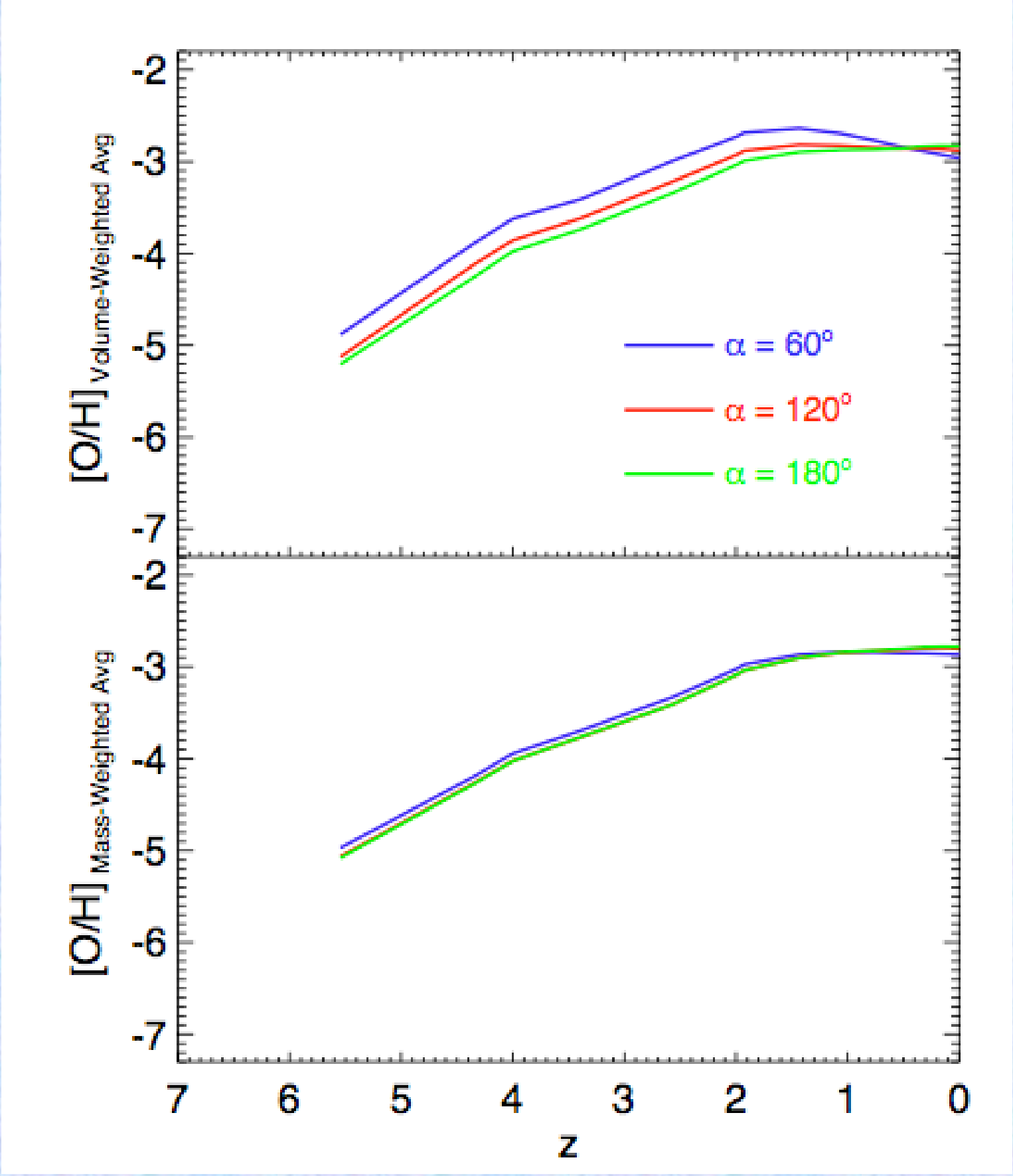


Fig. 2 --- Average IGM metallicity of [O/H] = –5 is produced at z = 5.5, which then rises gradually, and remains relatively flat at [O/H] = –2.8 between z = 2 and z = 0.

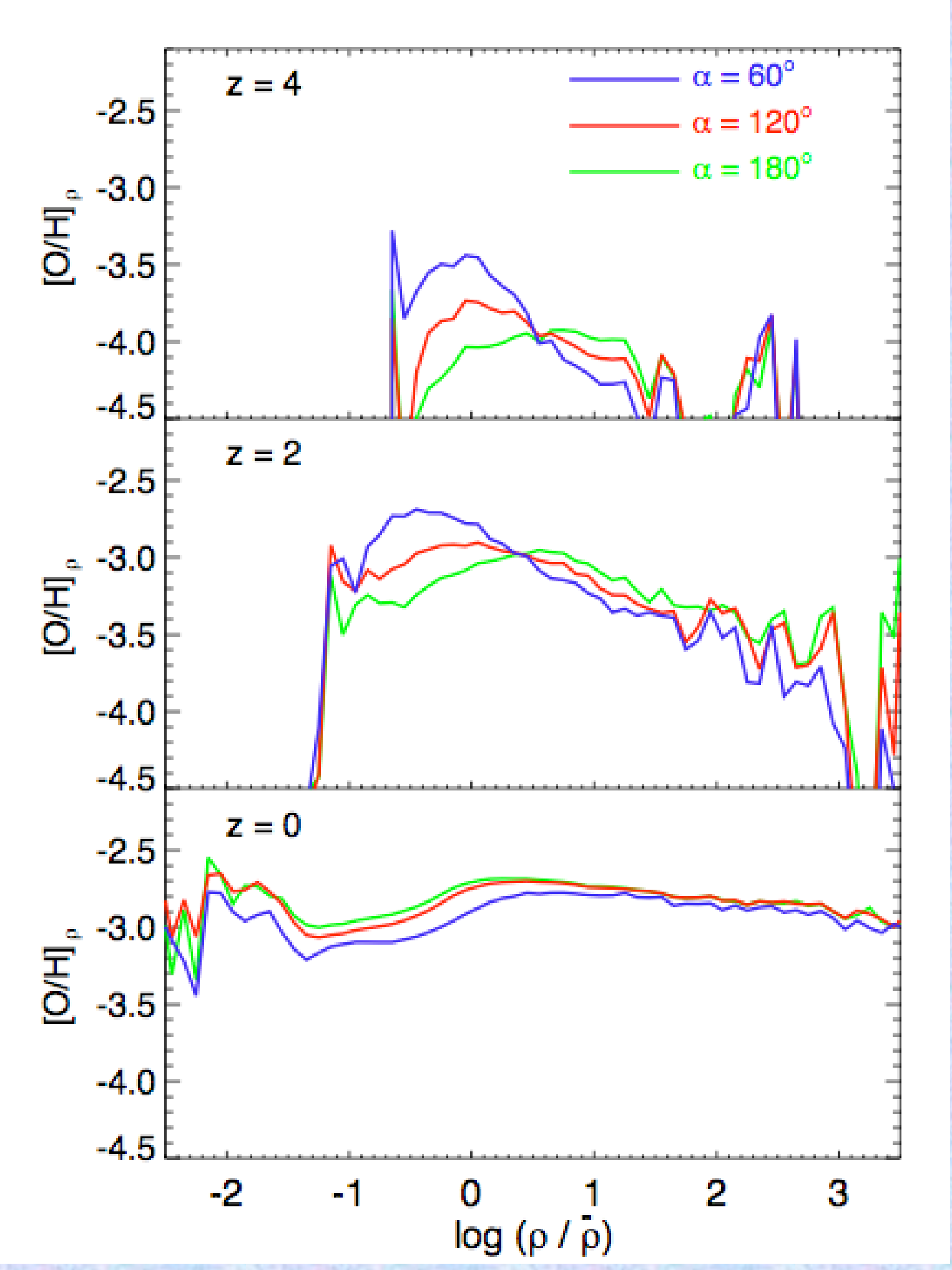


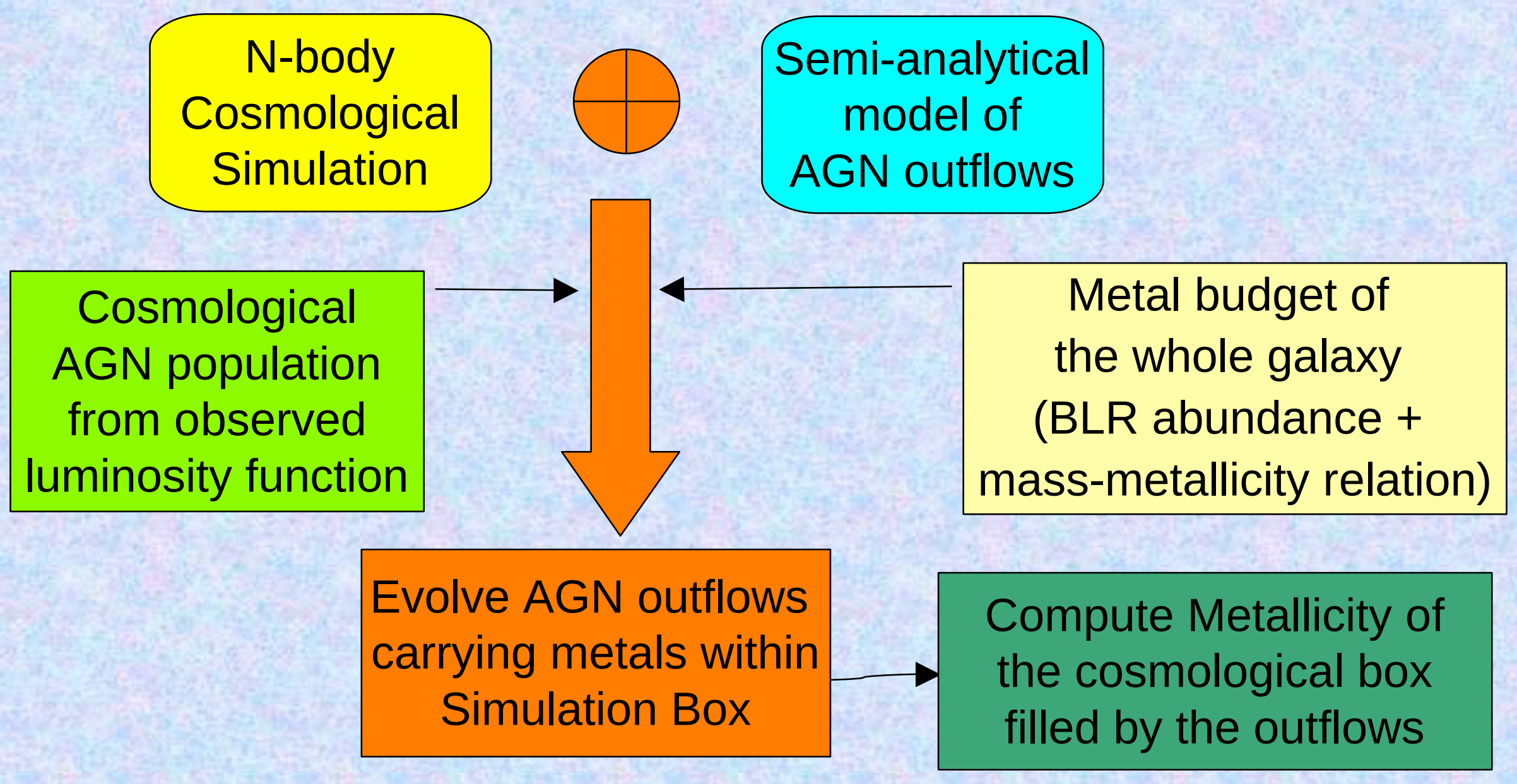
Fig. 6 --- Metallicity (at a given density) as a function of the total density of the IGM.

At early epochs (z = 4 & 2) the underdense regions are enriched to higher metallicities, and the induced metallicity decreases with increasing IGM density, a trend more prominent with increasing anisotropy of the outflows.

At z = 0, the metallicity is flat over all IGM densities.

Initially, more anisotropic outflows preferentially enrich low-density regions, but this trend gets eventually washed-out as the enriched volume fraction approaches unity.

Methodology



N-body Cosmological Simulation

Semi-analytical model of AGN outflows

Cosmological AGN population from observed luminosity function

Metal budget of the whole galaxy (BLR abundance + mass-metallicity relation)

Evolve AGN outflows carrying metals within Simulation Box

Compute Metallicity of the cosmological box filled by the outflows

Cosmological Simulation

- *N*-body (P^3M code) simulations of a cosmological volume of size (comoving) = 128 h^{-1} Mpc
- Evolve from $z = 25$ up to $z = 0$ in ΛCDM model (WMAP5)
- Redshift & Luminosity Distribution of sources from observed AGN bolometric luminosity function [5]
- Fraction of AGN hosting outflows, $f_{\text{outflow}} = 0.6$ [3]
- Distribute AGNs at local density peaks within simulation volume
- AGN outflows carry the metals produced by their host galaxies, & deposit those to the surrounding IGM volume permeated

Anisotropic Outflow Model

- Cosmological outflows expand anisotropically on large scales [7]
  - Away from high-density regions, into low-density regions
- Model outflow as Bipolar Spherical Cone [8]

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

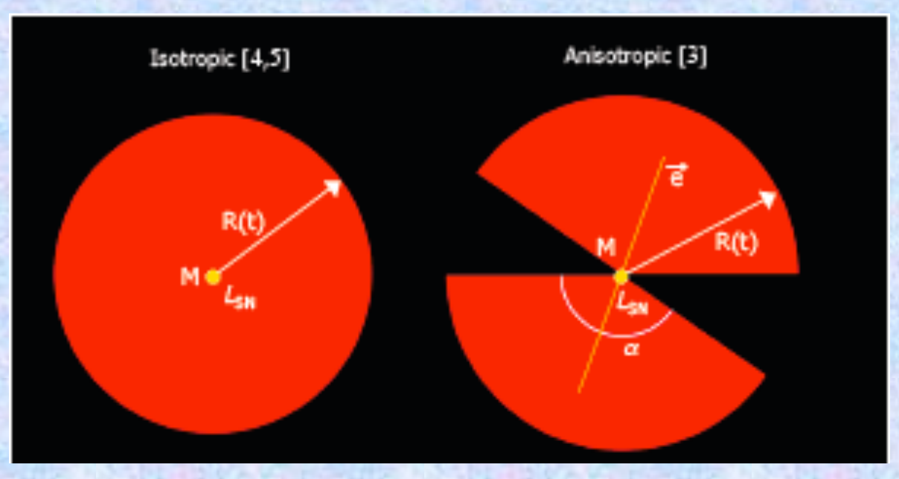


Fig. 1 --- Isotropic vs. anisotropic geometries of outflow.

- Outflow follows path of Least Resistance
  - Direction along which density drops the fastest
- Expansion equation : [4]

$$\ddot{R} = \underbrace{\frac{4\pi R^2}{M_S}\left(1-\cos\frac{\alpha}{2}\right)(p_T + p_B - p_x)}_{\text{Pressure gradient}} - \underbrace{\frac{G}{R^2}\left(M_d + M_{gal} + \frac{M_S}{2}\right)}_{\text{Gravitational deceleration}} + \underbrace{\Omega_\Lambda H^2 R}_{\text{Cosmological constant}} - \underbrace{\frac{\dot{M}_S}{M_S}\left(\dot{R} - v_p\right)}_{\text{Drag force}}$$

- Metals generated within galaxy by stars undergoing SNe

$$M_{Z,out} = \underbrace{5 Z_{Sun} M_{BH}}_{\text{Near the AGN (center of galaxy)}} + \underbrace{f_{esc} Z_G (1 - f_*) M_b}_{\text{Away from central AGN, in the rest of the galaxy [6]}}$$

Volume Enriched

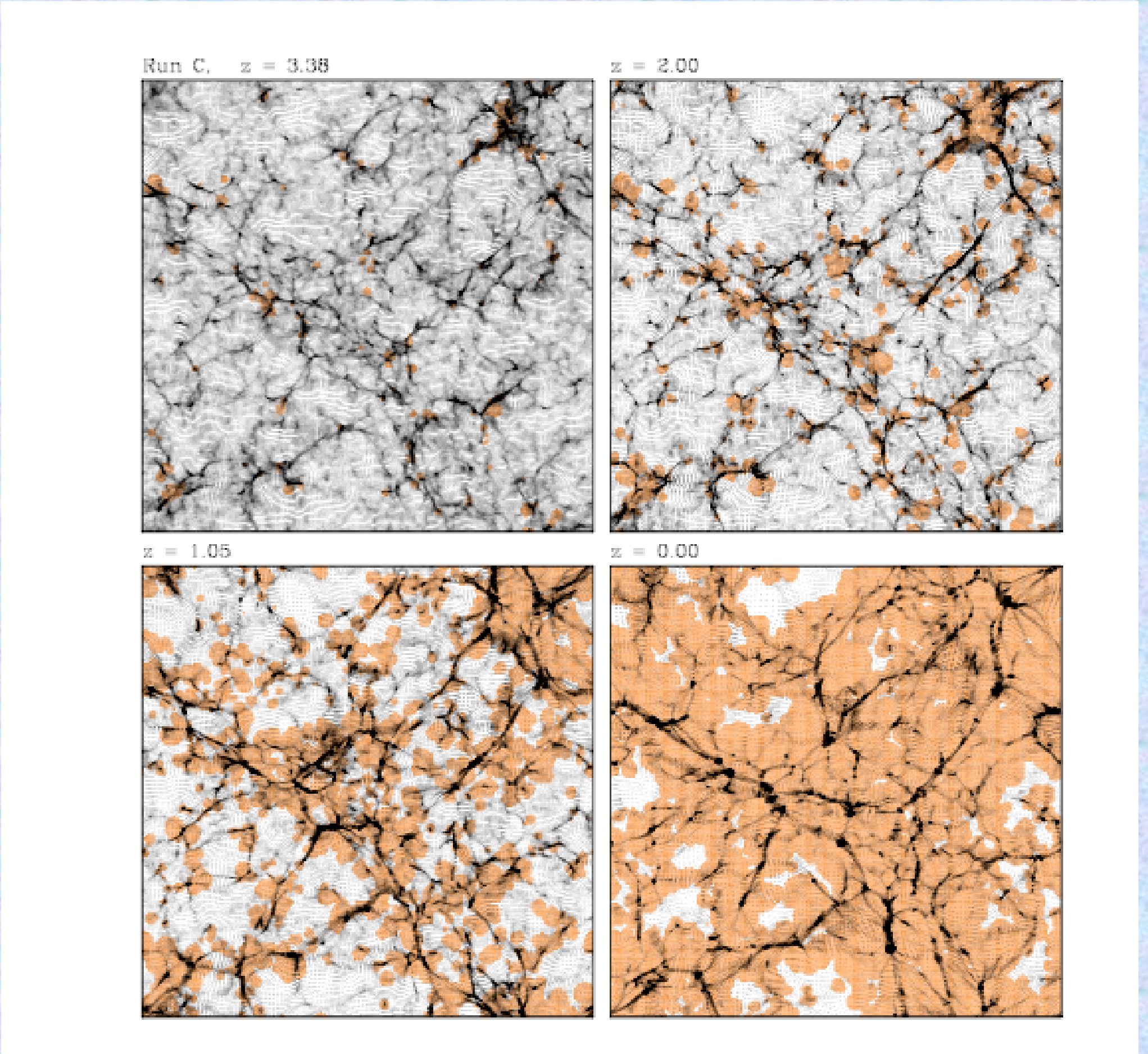


Fig. 3 --- Slice (of comoving size 128/h Mpc x 128/h Mpc x 2/h Mpc) off the computational volume (run C of [4]), depicting the redshift evolution of metal distribution. Orange areas show enriched volumes. Black dots represent the PM particles, showing the large-scale structures.

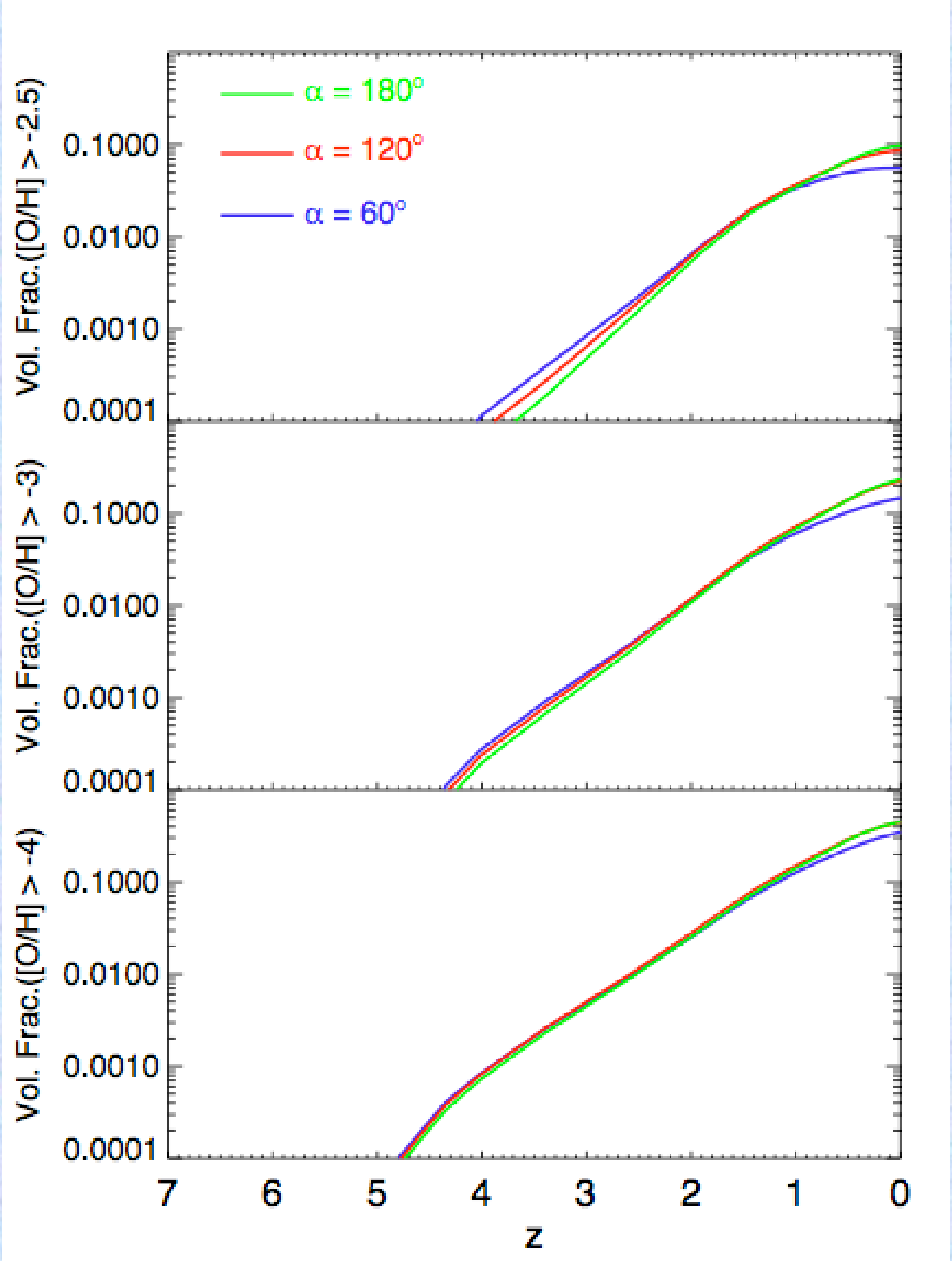


Fig. 4 --- Enriched IGM volume fractions are small at z > 3, then rises rapidly to the following at z = 0:
6–10% of the volume enriched to [O/H] > –2.5,
14–24% volume to [O/H] > –3, and
34–45% volume to [O/H] > –4.

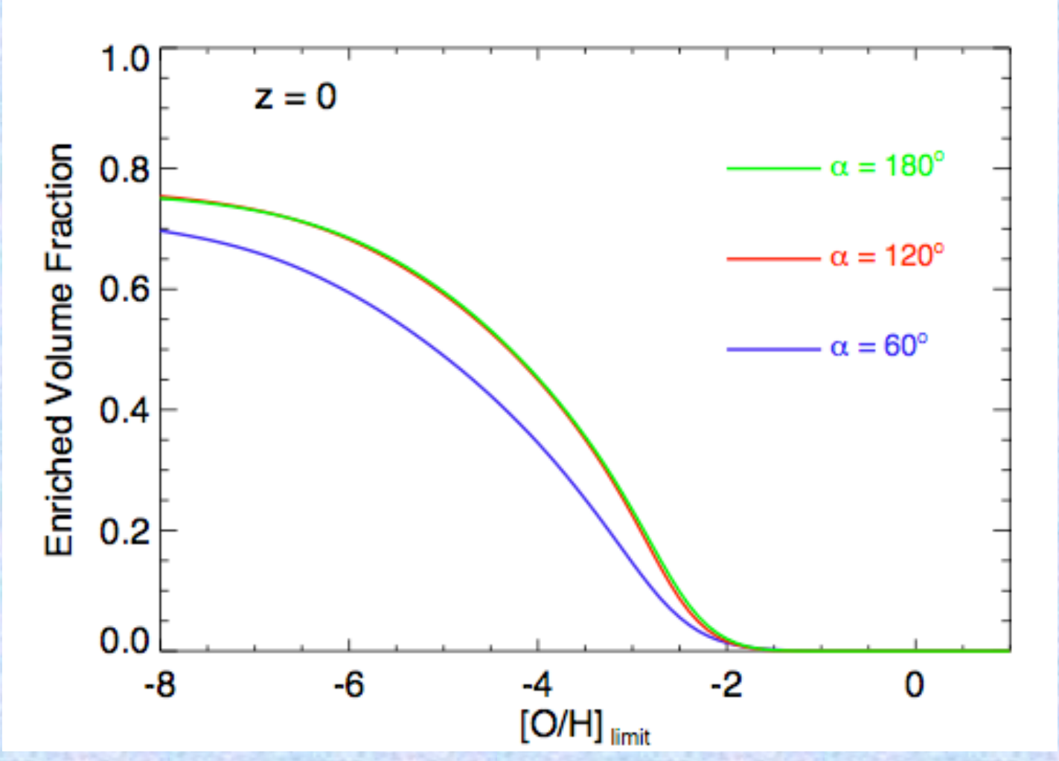


Fig. 5 --- Volume fractions enriched above a certain metallicity limit, V([O/H] > $[O/H]_{\text{limit}}$), at the present epoch. More than 60% of the volume is enriched to [O/H] > –6, and 1–2% of the volume is enriched to [O/H] > –2.

Conclusions

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

⌖ AGN outflows

➢ Permeate a total of 65 – 100% volume of the Universe by the present [4]

➢ Enrich the IGM with metals to > 10 – 20% of observed values [1]

⌖ Increasingly anisotropic outflows preferentially enrich underdense regions, esp. at higher redshifts

➢ Can explain observations of enriched low-density IGM at z ~ 3 – 4

References

[1] Barai, P., Martel, H. & Germain, J. 2010, submitted to ApJ
[2] Crenshaw, D.M., Kraemer, S.B. & George, I.M. 2003, ARA&A, 41, 117
[3] Ganguly, R. & Brotherton, M.S. 2008, ApJ, 672, 102
[4] Germain, J., Barai, P. & Martel, H. 2009, ApJ, 704, 1002
[5] Hopkins, P.F., Richards, G.T. & Hernquist, L. 2007, ApJ, 654, 731
[6] Maiolino, R. et al. 2008, A&A, 488, 463
[7] Martel, H. & Shapiro, P.R. 2001, RevMexAA, 10, 101
[8] Pieri, M.M., Martel, H. & Grenon, C. 2007, ApJ, 658, 36