Cosmological Impact of AGN Outflows Expanding Anisotropically on Large Scales

Abstract

We simulate anisotropic outflows from AGN and investigate their large-scale cosmological impact, by performing N-body simulations of ΛCDM Universe. A substantial fraction of AGN have been observed to host outflows powered by their central supermassive black holes. On large (Mpc) scales these energetic outflows are expected to move away from the high-density regions of large-scale structures (filaments and pancakes), with the outflowing matter getting channelled into low-density regions of the Universe. This causes an outflow to attain an anisotropic shape. The outflows expand and permeate significant volumes of the IGM, having feedback on further evolution of the filled volumes.

We implement semi-analytical prescriptions of such anisotropic AGN outflows within a cosmological volume. The observed quasar luminosity function is used to get the redshift and luminosity distribution of AGN populations, and analytical models are used for the outflow expansion. We compute the fractional volume of the simulation box filled by the anisotropic outflows of a cosmological population of AGN over the Hubble time, and the metallicity in the filled volumes. We explore the dependence of varying opening angle of the outflows on these large scale influence.

Paramita Barai (paramita.barai.1@ulaval.ca)

Joël Germain

Hugo Martel

Departement de physique, Université Laval, Quebéc City, QC, Canada

Centre de Recherche en Astrophysique du Quebec

Introduction

- Outflows are observed in a large fraction of Active Galactic Nuclei (AGN), in a wide variety of forms [1].
- AGN outflows play important roles in the formation and evolution of galaxies and large-scale structures, and the intergalactic medium (IGM).
  - Metal enrichment of the IGM leading to modifications of the cooling rate of star-forming gas.
  - Expulsion of proto-galactic gas by ram pressure stripping causing suppression of further star / galaxy formation.

➢ Goal : Investigate large-scale cosmological impact of AGN outflows over the Hubble time ([6], [9]).

➢ Calculate the volume fraction of the Universe filled, Metallicity in the filled volumes.

Redshift & Luminosity Distribution

- Observed AGN bolometric luminosity function [5].

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

- Constant AGN lifetime, $T_{AGN} = 10^8$ yr.
- Fraction of AGN hosting outflows, $f_{outflow} = 0.6$ [3].
- Locate AGN at local density peaks within simulation box.
  - Filter PM density above a minimum halo mass.

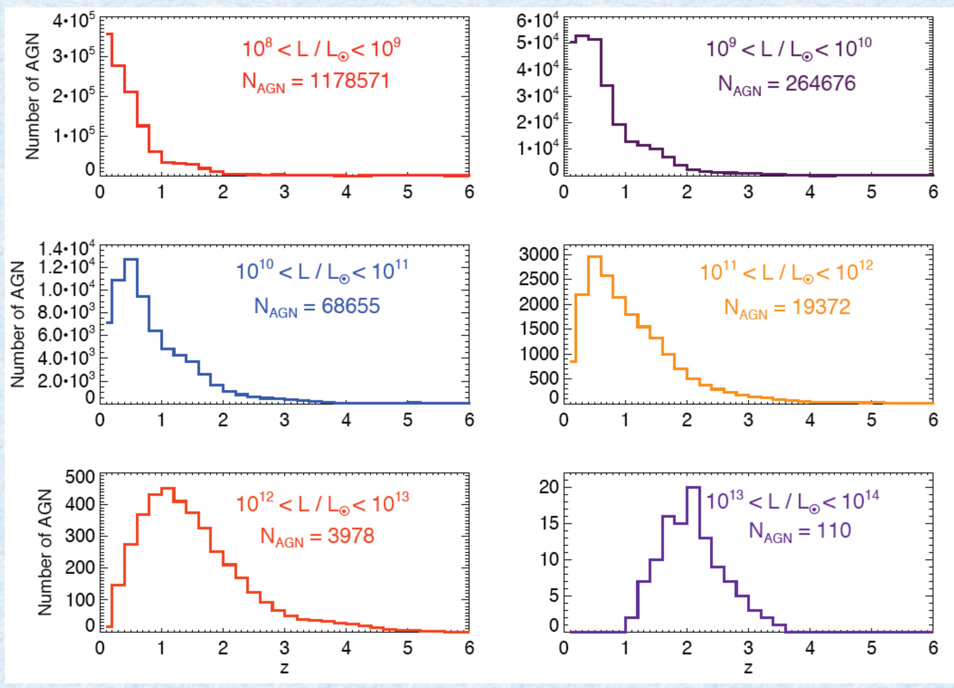


Fig. 3 --- All sources in box from QLF. $N_{AGN,total}$ = 1535362.

Volume Enriched / Filled

- We use a SPH smoothing algorithm to get the density and metallicity on a grid.
- Each particle is ascribed a Smoothing Length h, and is considered to be spread over a spherical volume of radius $1.7h$
- Filling factor grid : $N_{ff}^3 = 256^3$
- Count the mesh cells in the simulation box occurring inside the spherical volume of one or more enriched particles.
- Total number of filled cells, N_{AGN}
  ⇒ Total volume of box occupied by outflows.
- Volume fraction of box enriched by outflows = N_{AGN} / N_{ff}^3

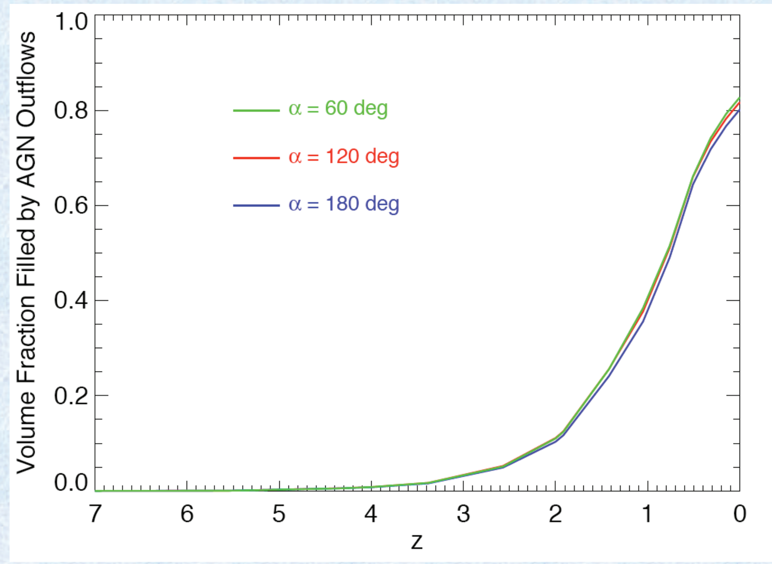
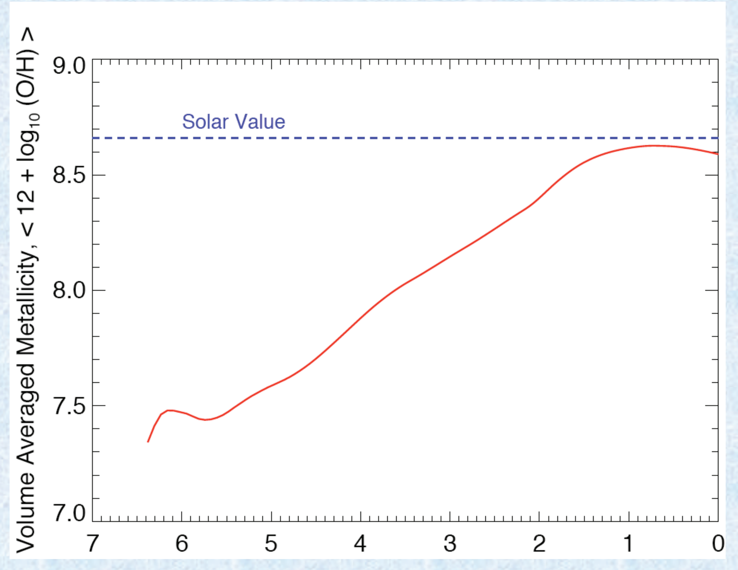


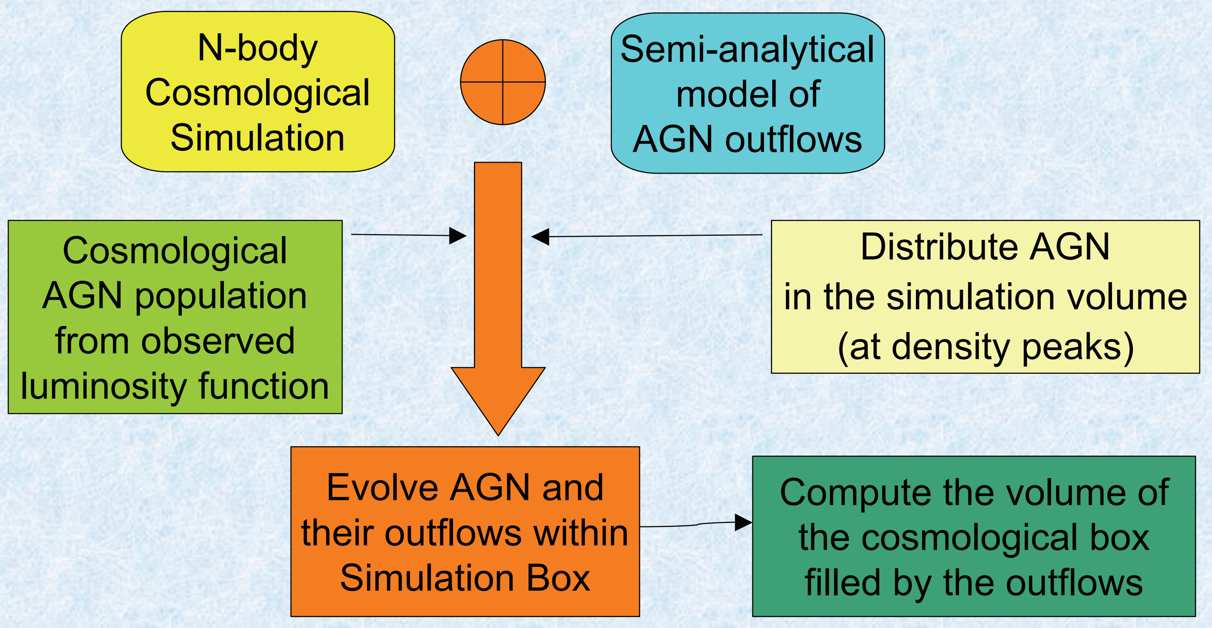
Fig. 6 --- Volume filling fractions (for different opening angles).



$$\left\langle \frac{O}{H} \right\rangle = \frac{\sum \left(\frac{O}{H}\right) V}{\sum V}$$

Fig. 7 --- Volume averaged metal abundance values in the volumes filled by outflows.

Methodology



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, [4]).

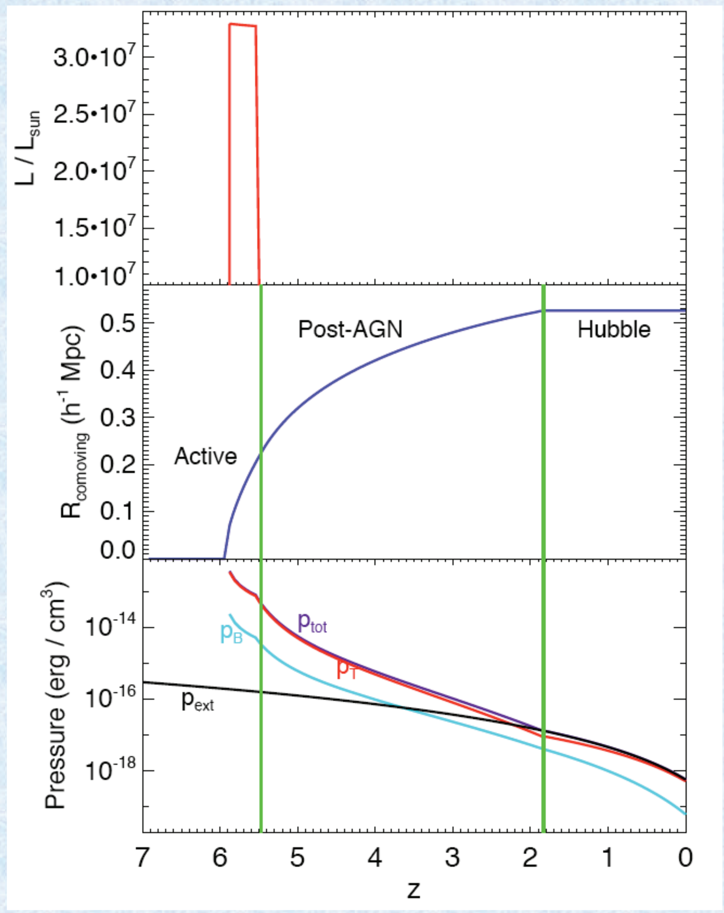


Fig. 4 --- Evolution of a single outflow. Top: total luminosity, Middle: Comoving radius, Bottom: Pressures (external IGM, magnetic, thermal and total outflow). Vertical green lines separate phases of expansion - active, post-AGN and Hubble.

Analytical Model for Anisotropic Outflow

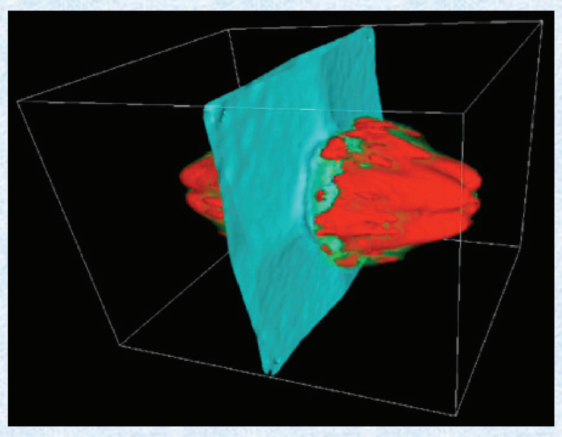


Fig. 1 --- SPH simulation of an explosion in a galaxy.
Blue: density iso-surface, showing the cosmological pancake.
Red: temperature iso-surface, showing the outflow.

Cosmological outflows expand anisotropically in large scales [7].
- Away from high-density regions, into low-density regions, along the path of least resistance.
- Model outflow as Bipolar Spherical Cone [8].

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

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

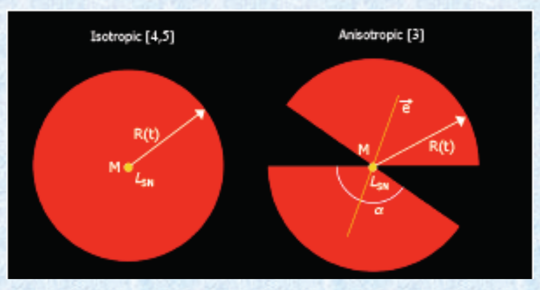


Fig. 2 --- Isotropic and anisotropic geometries of outflow.

- Outflow follows path of Least Resistance.
  - Direction along which density drops the fastest as we move away from the AGN location peak.
- Expansion equation: ([2], [10])

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

Pressure gradient — Gravitational deceleration — Cosmological constant — Drag force

- Thermal pressure:

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

Thermal energy injection — Outflow expansion

- Magnetic pressure:

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

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.

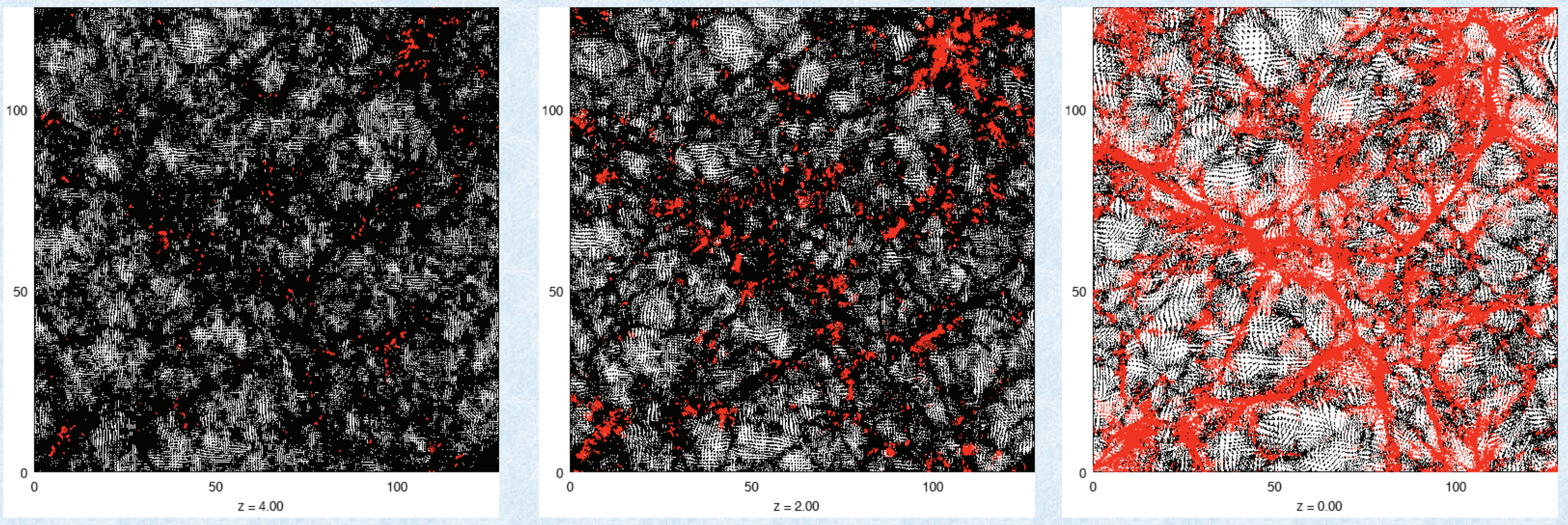


Fig. 5 --- A 4 Mpc wide slice of the box at different redshifts. Black dots: Non-enriched particles, Red dots: Enriched particles.

Conclusions

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

⌖ AGN outflows are found pervade 80% of the volume of the Universe by the present.

⌖ Volume averaged metallicity in the filled regions reaches almost Solar value at $z \sim 1$.

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

References

[1] Crenshaw, D.M., Kraemer, S.B. & George, I.M. 2003, ARA&A, 41, 117
[2] Furlanetto, S.R. & Loeb, A. 2001, ApJ, 556, 61
[3] Ganguly, R. & Brotherton, M.S. 2008, ApJ, 672, 102
[4] Hinshaw, G. et al. 2008, arXiv: 0803.0732
[5] Hopkins, P.F., Richards, G.T. & Hernquist, L. 2007, ApJ, 654, 731
[6] Levine, R. & Gnedin, N.Y. 2005, ApJ, 632, 727
[7] Martel, H. & Shapiro, P.R. 2001, RevMexAA, 10, 101
[8] Pieri, M.M., Martel, H. & Grenon, C. 2007, ApJ, 658, 36
[9] Scannapieco, E. & Oh, S.P. 2004, ApJ, 608, 62
[10] Tegmark, M., Silk, J. & Evrard, A. 1993, ApJ, 417, 54