Large Scale Anisotropic Expansion of AGN Outflows in Cosmological Simulations

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The Interface between Galaxy Formation and AGNs (Vulcano, Italy)

Introduction

- Outflows observed in a large fraction of AGNs

- <u>Goal:</u> Calculate the volume fraction of the Universe filled by AGN outflows over the Hubble time
  - Energy density
  - Magnetic field

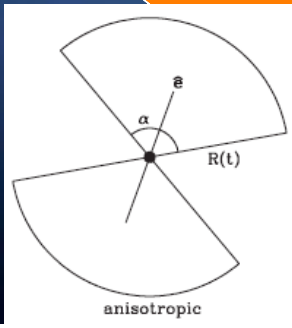
Motivation

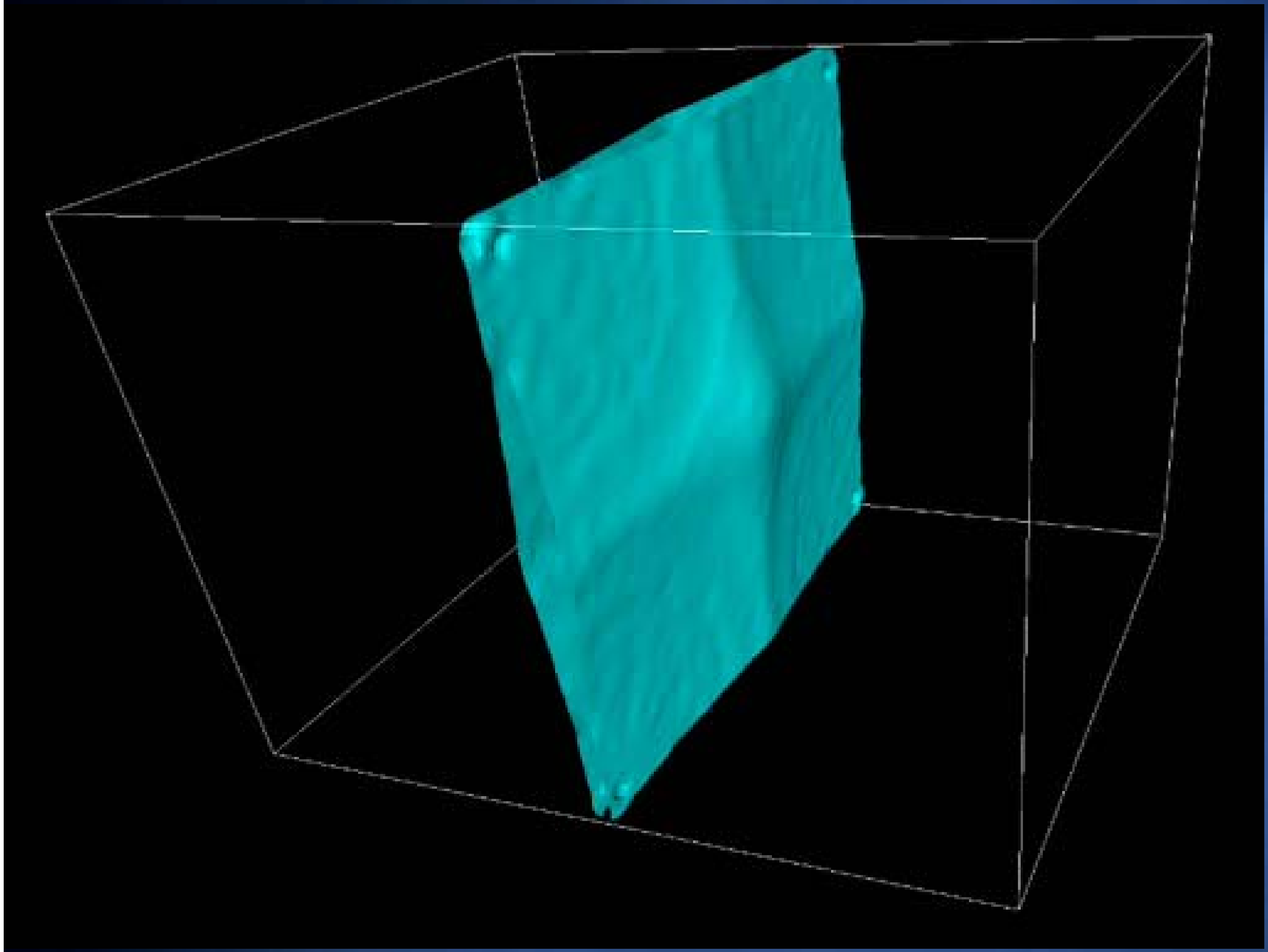
- Previous studies
  - Furlanetto & Loeb 2001, ApJ, 556, 619
  - Scannapieco & Oh 2004, ApJ, 608, 62
  - Levine & Gnedin 2005, ApJ, 632, 727

Spherical Outflow

Our Improvement

- Anisotropically expanding outflow
- Implement in cosmological simulations





Anisotropic Outflow

- Cosmological outflows expand anisotropically in large scales
- Away from high-density regions, into low-density regions, along the path of least resistance

(Martel & Shapiro 2001, RevMexAA, 10, 101)

Outflow Geometry

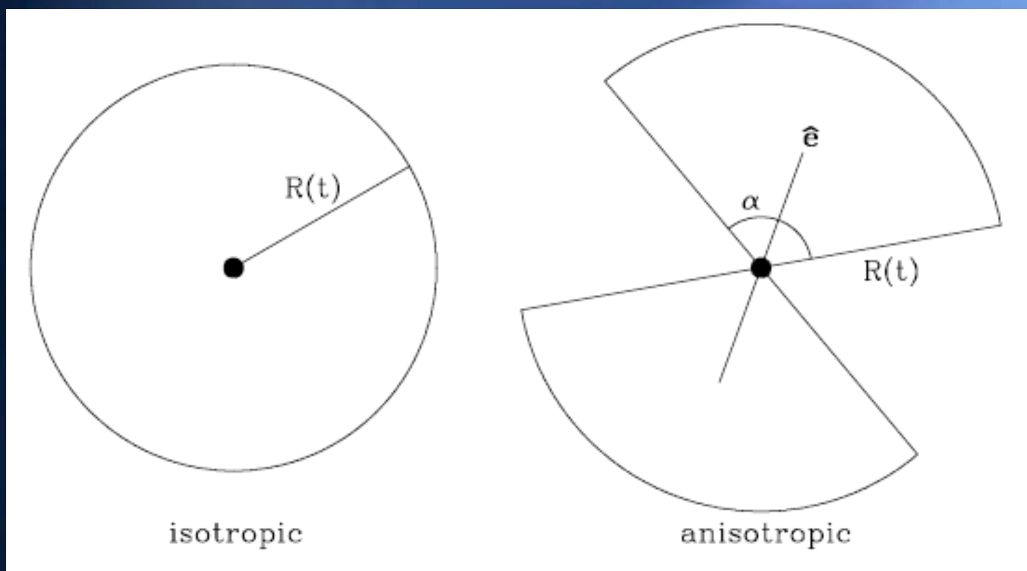
(Pieri, Martel & Grenon 2007, ApJ, 658, 36)

- Bipolar spherical cone
- Spherical coordinates (r, θ, ϕ)

$$r \le R$$

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

$$0 \le \phi < 2\pi$$



- Radius = R
- Opening angle = α
- Direction of Outflow = $\hat{e}$ (unit vector)

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

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

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

Methodology

N-body Cosmological Simulation

Semi-analytical model of AGN outflows

Cosmological AGN population from observed luminosity function

Distribute AGN in the simulation volume (at density peaks)

Evolve AGN and their outflows within Simulation Box

Compute the volume of the cosmological box filled by the outflows

Cosmological Simulation

- N-body simulations of a cosmological volume
- Box size (comoving) = 128 h^{-1} Mpc
  - Triply periodic boundary conditions
  - Expanding with the Hubble flow
- 256^3 dark matter particles
- 512^3 grid
- Evolve from z=25 up to z=0
- P^3M code (particle-particle/particle-mesh)

- Grav. softening length = 0.3 × cell size = 75 h^{-1} kpc
- Particle mass = $1.32 \times 10^{10}\ M_\odot$
- ΛCDM model :

$$\Omega_M = 0.241$$
$$\Omega_B = 0.0416$$
$$\Omega_\Lambda = 0.759$$
$$H_0 = 73.2 \text{ km s}^{-1} \text{ Mpc}^{-1}$$
$$n_s = 0.958$$
$$T_{CMB} = 2.725 \text{ K}$$

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 :

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

Redshift & Luminosity Distribution

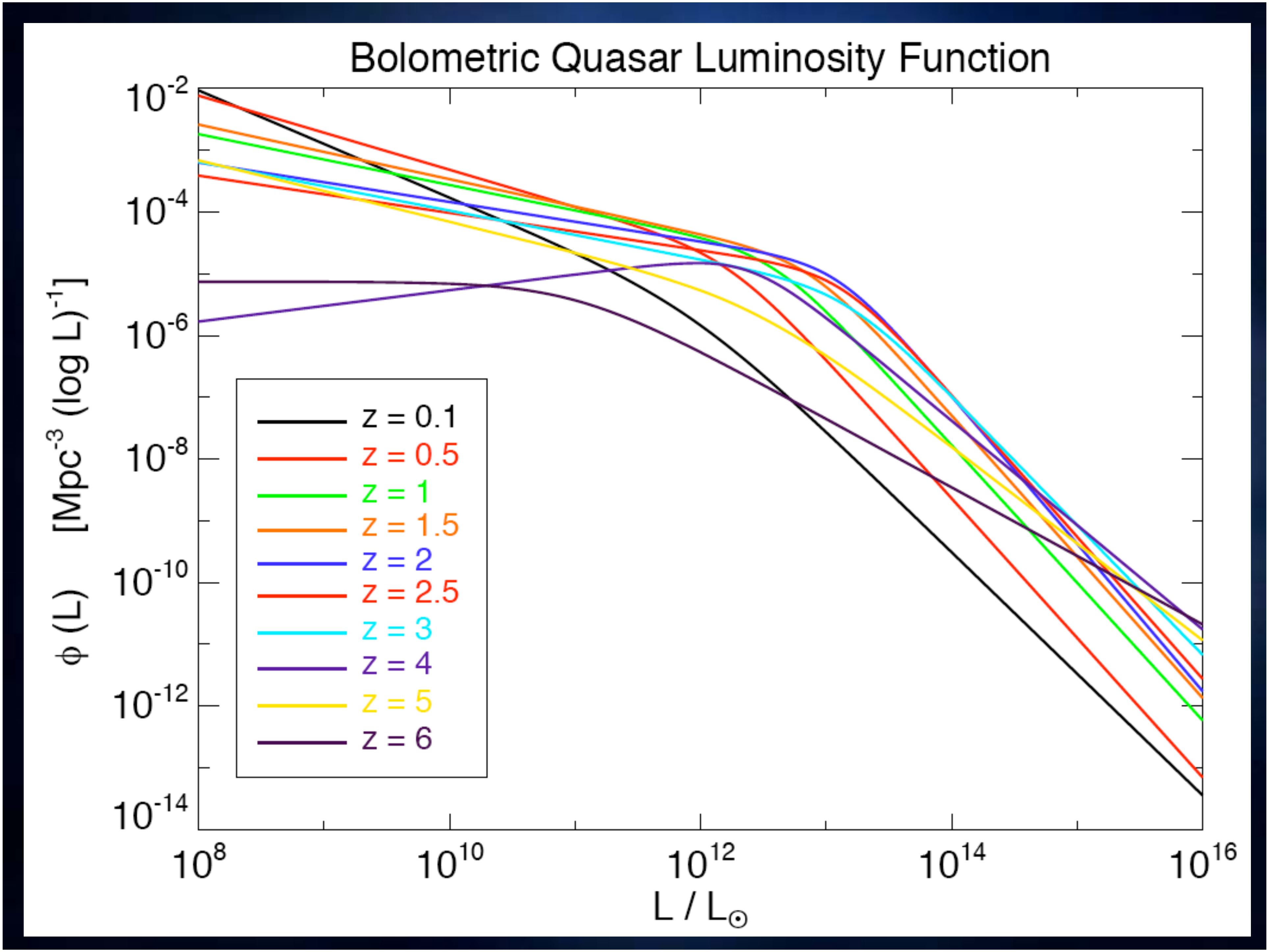
- Observed AGN bolometric luminosity function
  (Hopkins, Richards & Hernquist 2007, ApJ, 654, 731)

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

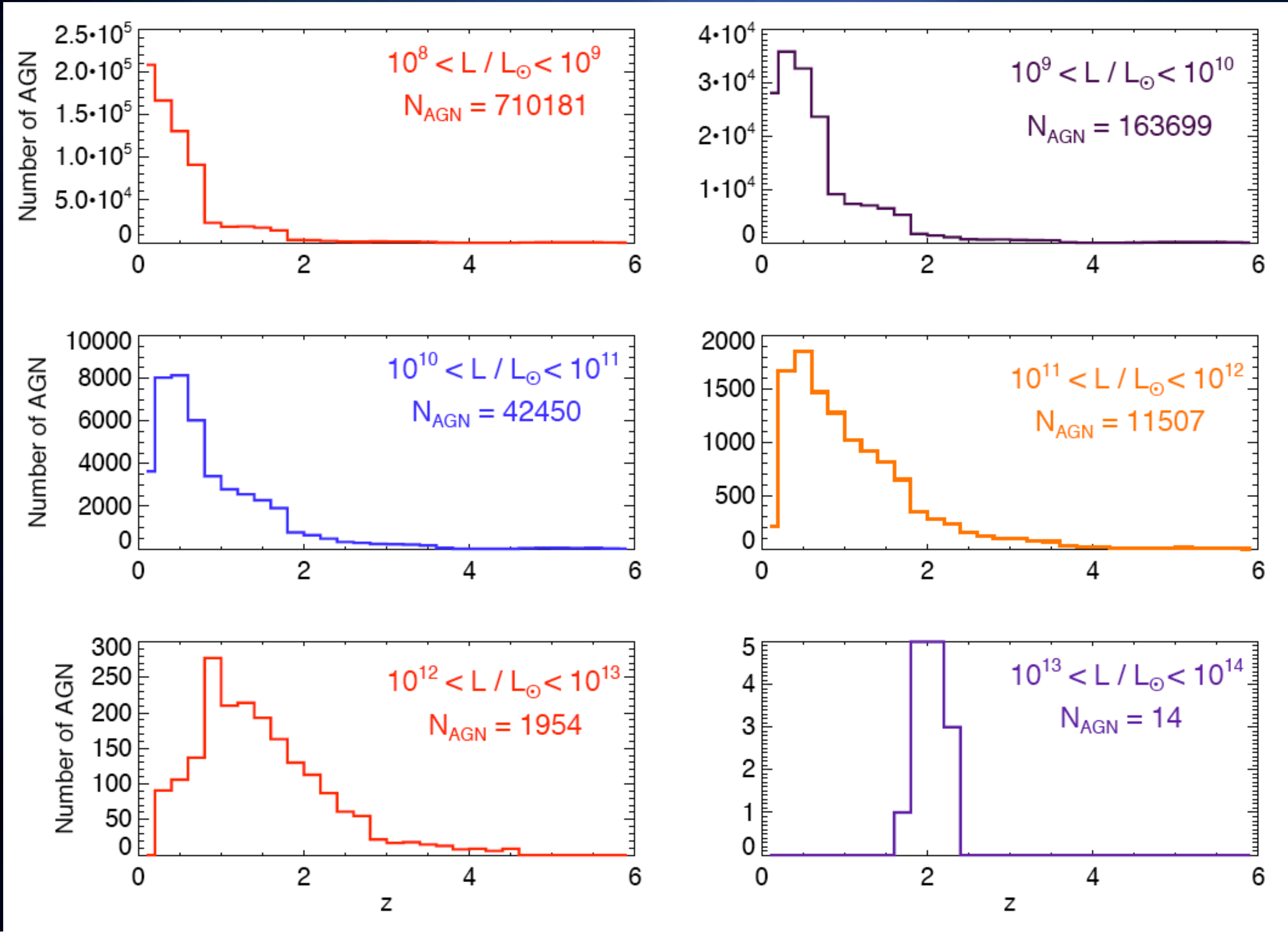
- Constant AGN lifetime, $T_{\mathrm{AGN}} = 10^8$ yr
- Fraction of AGN hosting outflows = 0.2
- Number of AGN

$$dN = f_{\mathrm{outflow}}\varphi(L)d[\log L]V_{\mathrm{box}}$$

- Locate AGN at local density peaks
  - Filter density above a minimum halo mass

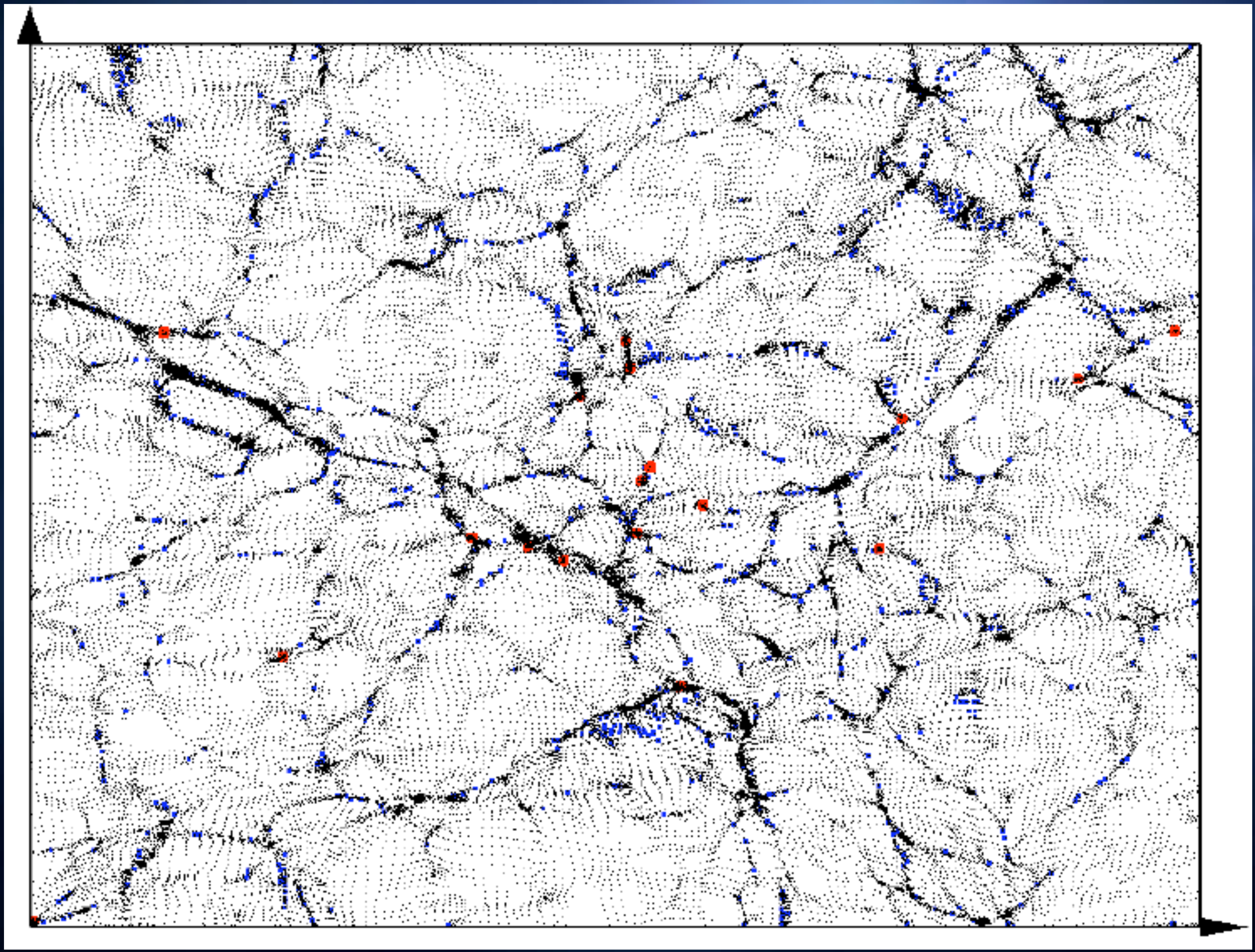

Bolometric Quasar Luminosity Function
φ (L) [Mpc^-3 (log L)^-1]
L / L☉
10^-2
10^-4
10^-6
10^-8
10^-10
10^-12
10^-14
10^8
10^10
10^12
10^14
10^16
z = 0.1
z = 0.5
z = 1
z = 1.5
z = 2
z = 2.5
z = 3
z = 4
z = 5
z = 6

All Sources in Box from QLF. $N_{AGN,total}$ = 929805



New AGN locations in a slice of box at z = 0.5

Black - Particles (PM), blue - Peaks, red - AGNs



Active-AGN Life

- Jet Kinetic power

$$L_K = \varepsilon_K L_{bol}/2,$$
$$\text{with, } \varepsilon_K = 0.1$$

- Jet advance

$$\frac{L_K}{A_s c} = \rho_x \left(\frac{dR}{dt}\right)^2$$

- Energy

$$E = 2 L_K t_{age}$$

- Pressure

$$pV = (\Gamma - 1)E$$

  - Relativistic outflow with $\Gamma = 4/3$

- Overpressured : $p >> p_x$

Post-AGN Evolution

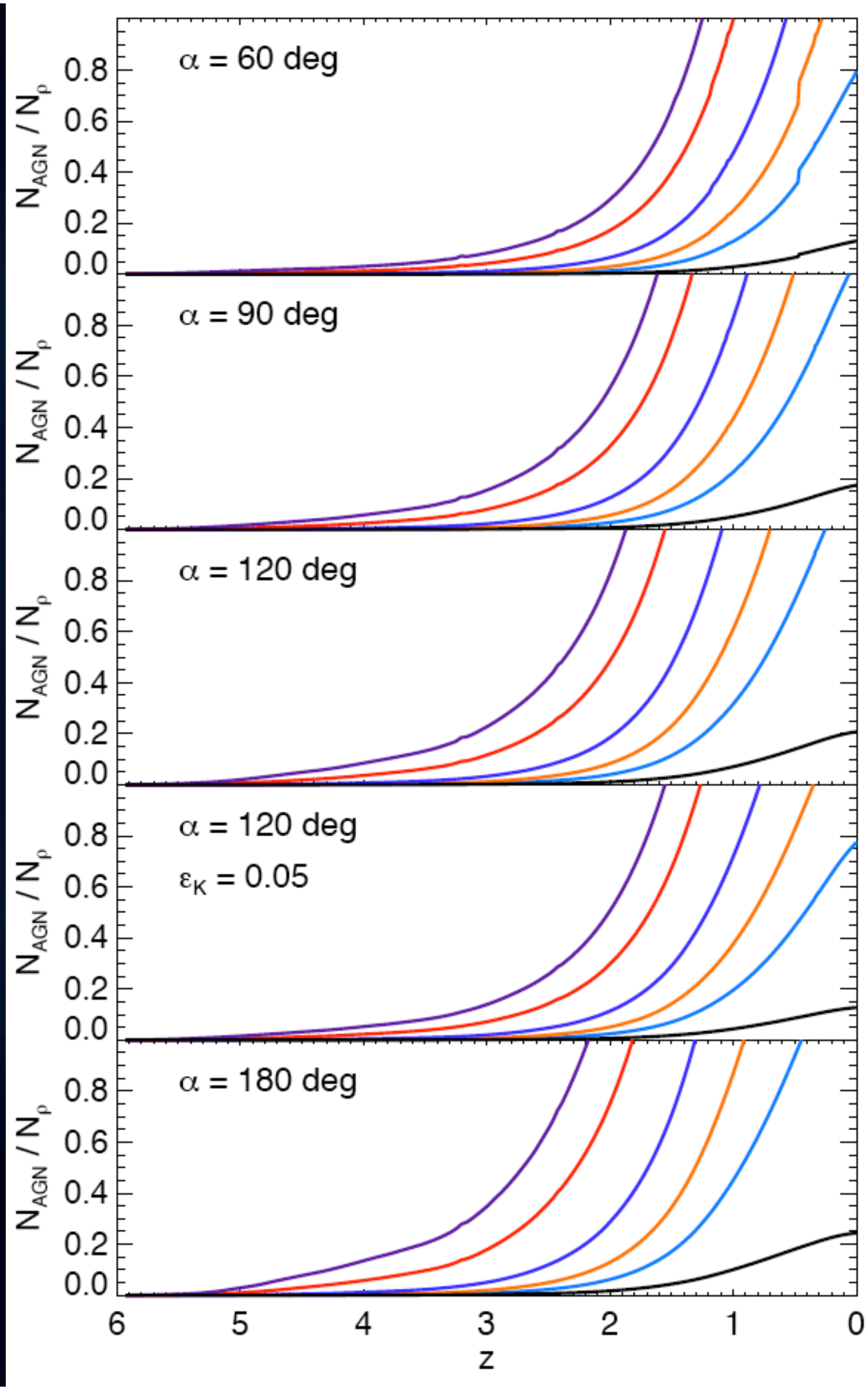
- Anisotropic Expansion when overpressured, $p > p_x$
  - Sedov-Taylor adiabatic expansion
    $$R = \xi_0 \left(\frac{E_{AGN} t_{age}^2}{\bar{\rho}_x} \right)^{1/5}$$
  - Total AGN energy
    $$E_{AGN} = 2 L_K T_{AGN}$$
  - Adiabatic loss
    $$p R^{3\Gamma_x} = \text{constant}$$
  - Bipolar conical outflow
    $$V = \frac{4}{3} \pi R^3 \left(1 - \cos \frac{\alpha}{2} \right)$$
- When reach pressure equilibrium, $p = p_x$
  - Passive Hubble evolution, R_{comoving} = Constant

Volume Filled

- Count mesh cells in the simulation box occurring inside the volume of one/more outflow
- Total number of filled cells, N_{AGN} = total volume of box occupied by outflows
- Express the total volume filled as a fraction of volumes of various overdensities in the box

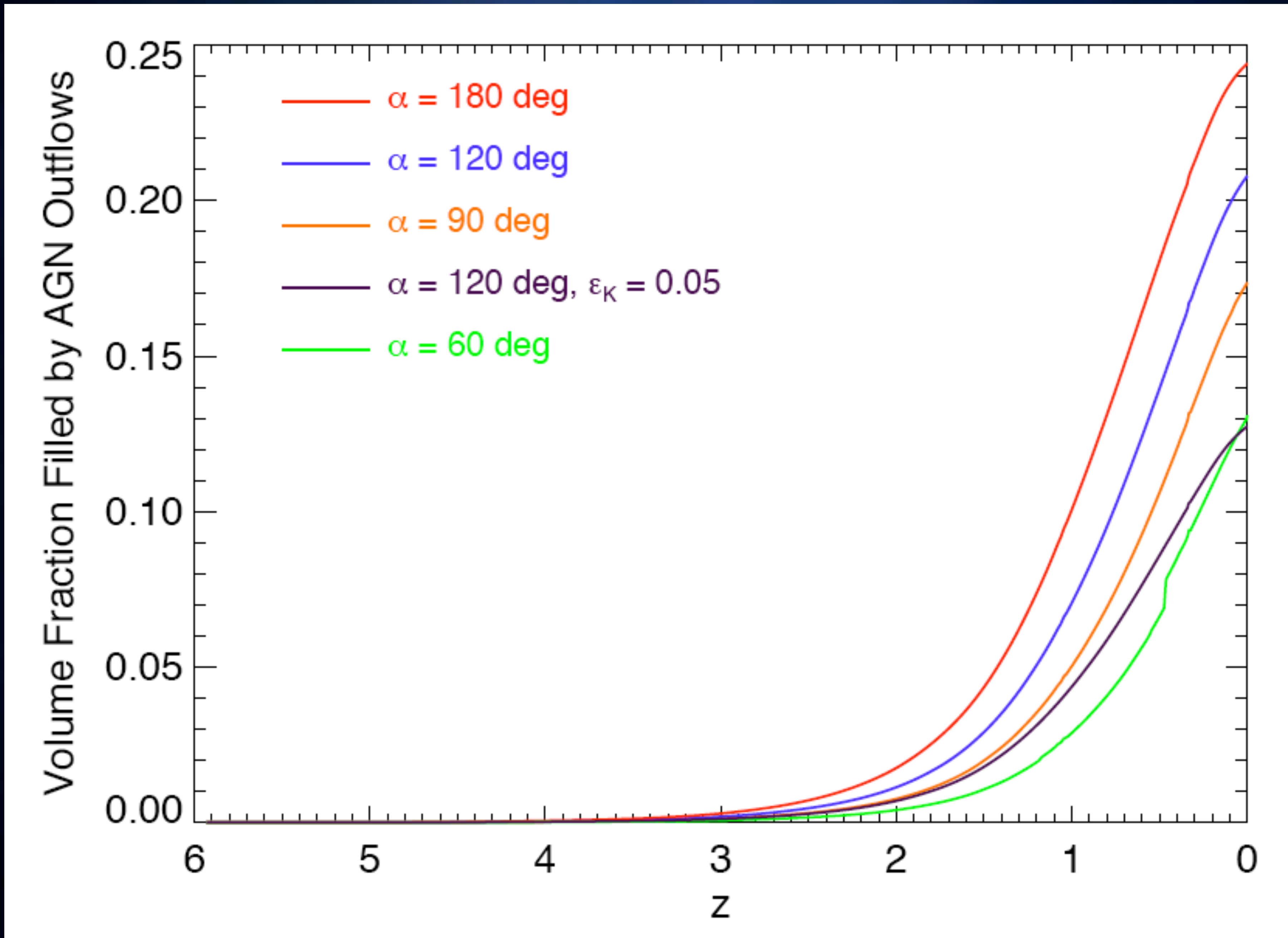
$$N_{\rho} = N\left(\rho > C\rho_{mean}\right)$$

$$\rho_{mean} = \left(1 + z\right)^{3} \Omega_{M} \frac{3H_{0}^{2}}{8\pi G}$$



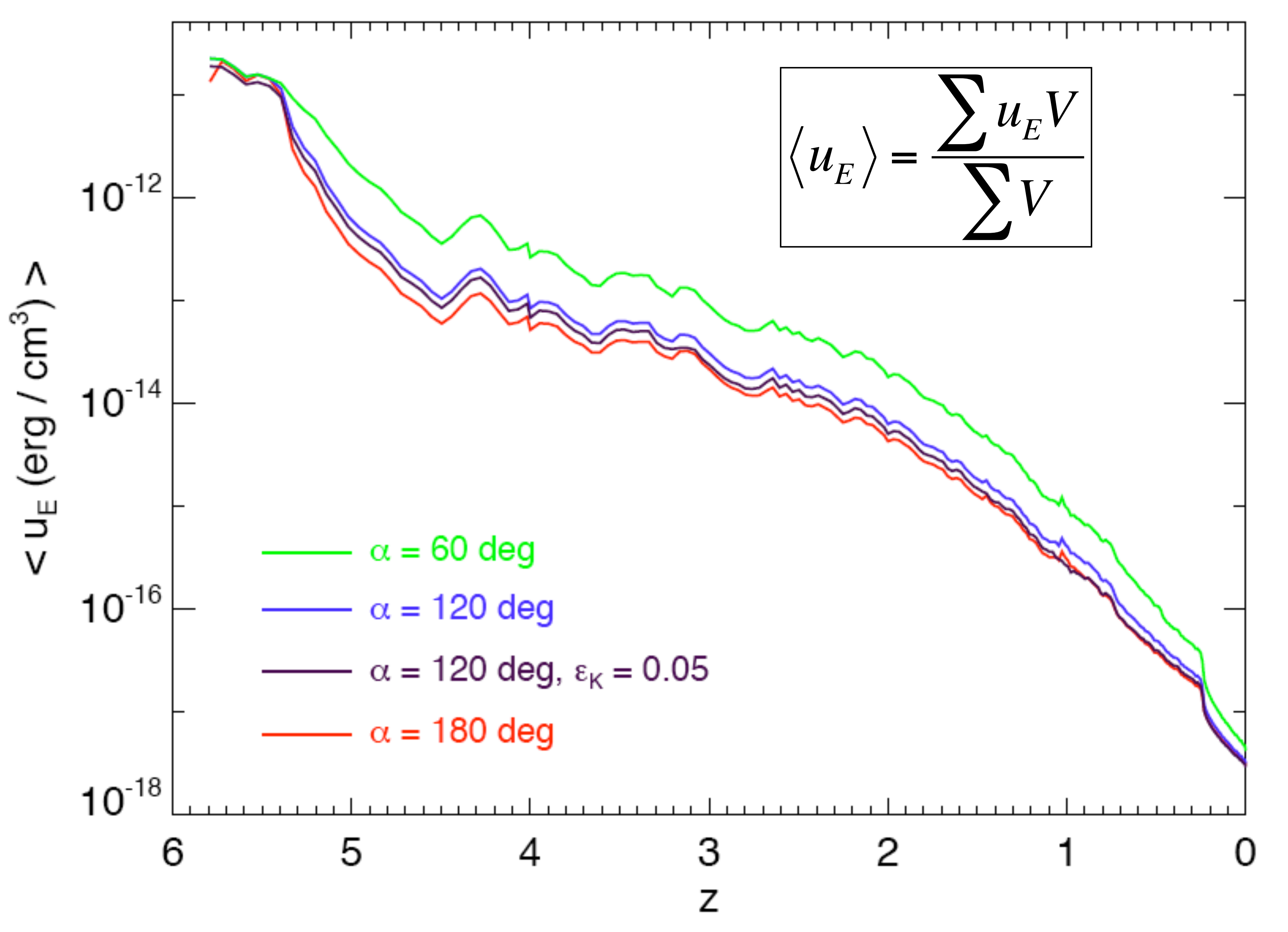
Fractional Volumes of box of various overdensities filled by AGN outflows

(N_ρ with C = 0, 1, 2, 3, 5, 7)

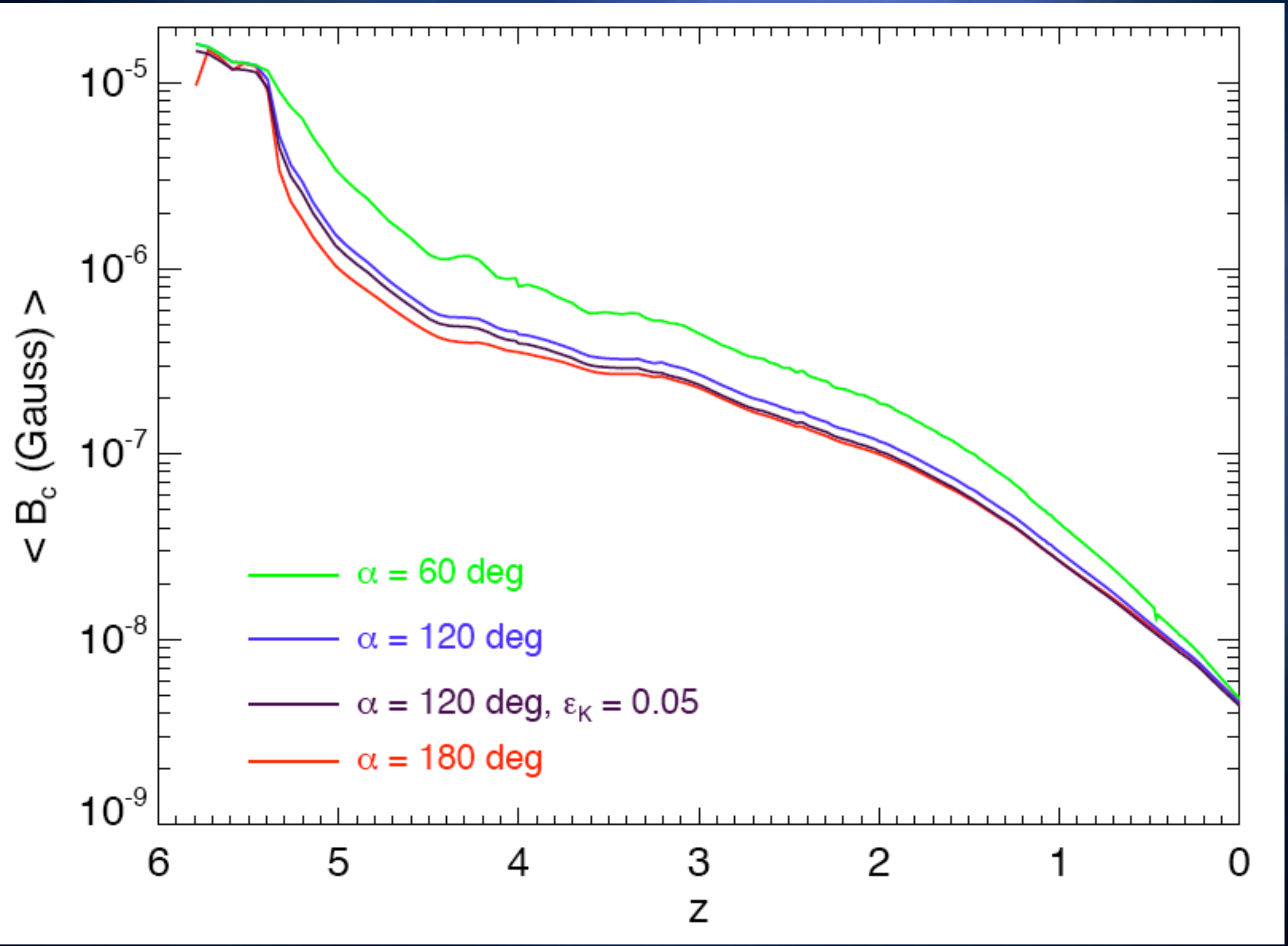


α = 180 deg
α = 120 deg
α = 90 deg
α = 120 deg, εK = 0.05
α = 60 deg
Volume Fraction Filled by AGN Outflows
0.25
0.20
0.15
0.10
0.05
0.00
6
5
4
3
2
1
0
z

Volume Averaged Energy Density



Volume Averaged Magnetic Field



Summary

- Implemented a semi-analytical model of anisotropic AGN outflows in N-body simulations
- AGN outflows pervade 13 – 24% of the volume of the Universe by the present
  - In some cases occupy 100% of the overdense regions by $z > 0$
- Volume averaged quantities in the filled regions at $z = 0$
  - Energy Density = 5×10^{-18} erg cm^{-3}
  - Magnetic field = 10^{-9} Gauss

References

- Furlanetto, S.R. & Loeb, A. 2001, ApJ, 556, 619 (FL01)
- Ganguly, R. & Brotherton, M.S. 2008, ApJ, 672, 102
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- Scannapieco, E. & Oh, S.P. 2004, ApJ, 608, 62