Cosmological Simulations to Investigate Active Galaxy Outflow Propagation and Metal Enrichment on Large-Scales

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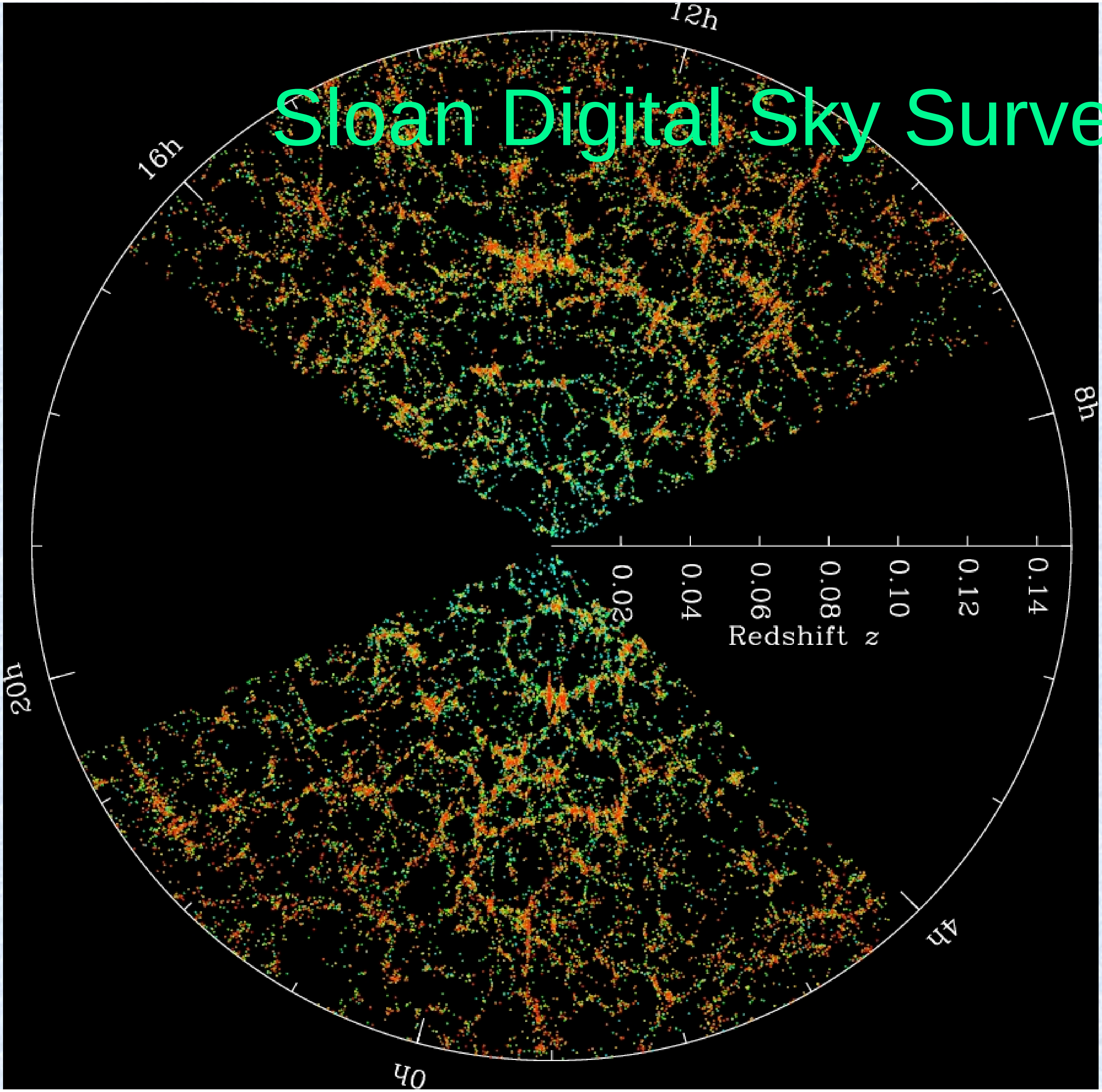
Outline

- Introduction
  - Trends from observations
  - Modeling galaxy formation & large-scale structures in simulations

- My work :

  AGN Outflows in a Cosmological Volume
  - Methodology
  - Simulation
  - Results : IGM Volume Enriched & Metallicity

Sloan Digital Sky Survey



- Credit:

  M. Blanton & SDSS team

- Ref. - Poster by Prakash Sarkar

Galaxy Formation Modeling

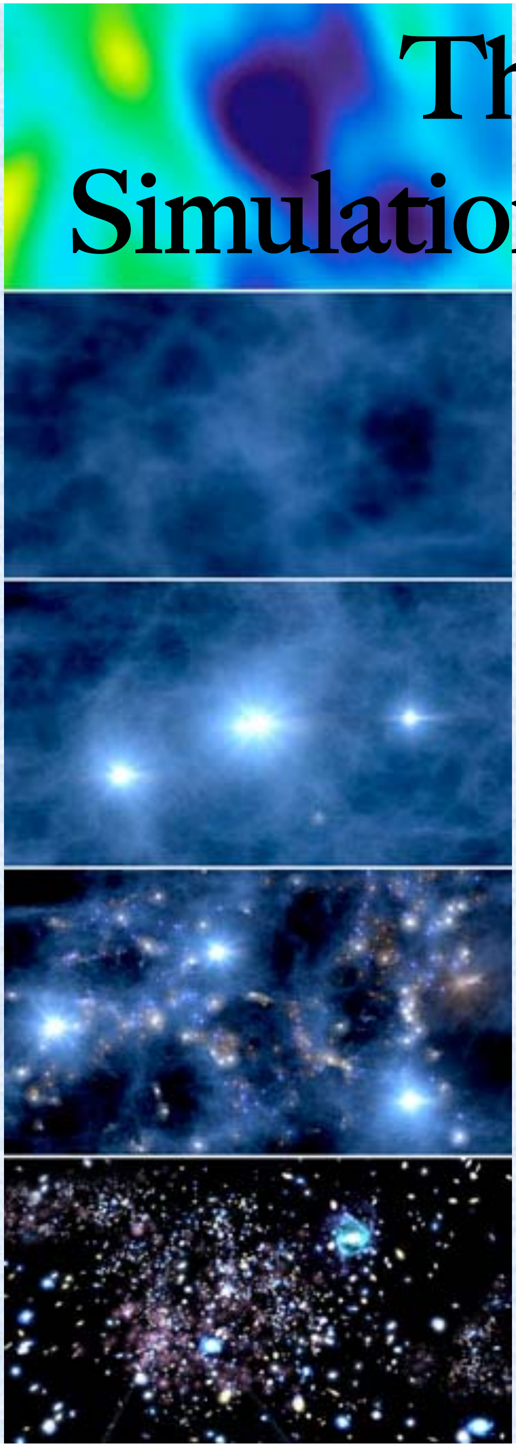
Cosmological Hydrodynamic Simulations

Large Scale Structure Formation

- Quantum fluctuations shortly after the Big Bang created primordial density perturbations
  - Inflation expands the perturbations, which form the seeds for later growth
- Gravitational clumping of matter from these initial density fluctuations ⇒ Structures grow

- Main forces driving evolution
  - Gravity : affects dark matter and baryons
  - Gas dynamics : only baryons

The Universe in a Box: Simulations of Large Scale Structures



- Purpose: Model the growth of structures
- Numerical Simulations are the only experiments to verify theories of the origin and evolution of the Universe
- Can run many experiments over cosmic epochs in practical times

How to Simulate?

- A computational box ⇔ the Universe
- Particles in the box ⇔ matter in the Universe
- Assume: can model LSS in terms of massive particles each representing about 10^8 - 10^9 $M_\odot$

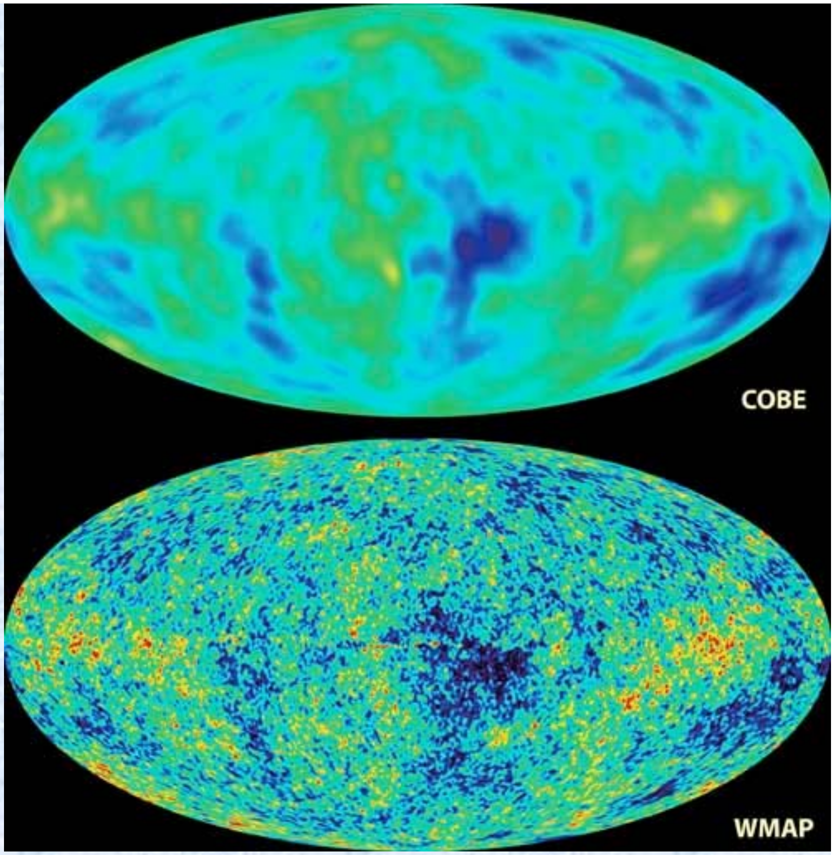
- Two-fold process:
  - Generate the initial conditions
  - Numerically evolve particles in computational box using non-relativistic dynamical equations

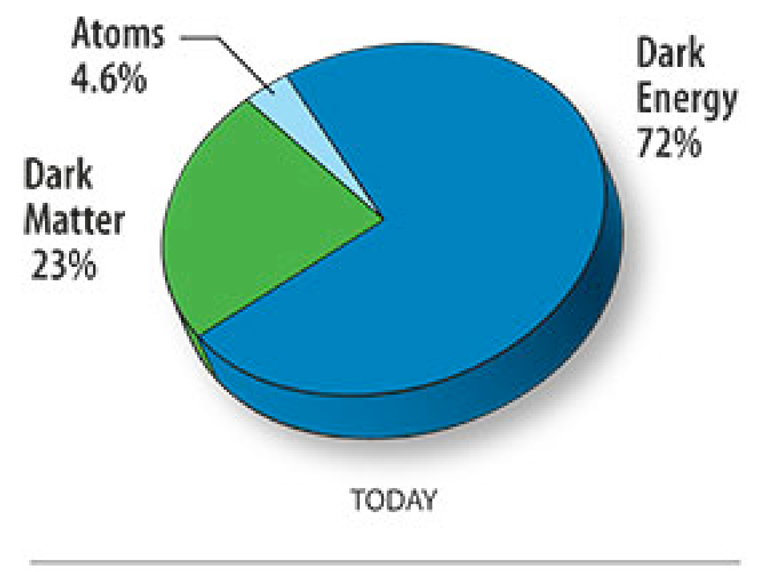
- Run in supercomputers
  - High speed & processing power, weeks - months of time

- <u>Goal:</u> get the final particle distribution consistent with observations of the Universe

Initial Condition

- Cosmological model well constrained by obs.
  - CMBR (WMAP)
  - SN
  - Galaxy clusters
  - Gravitational lensing
- ΛCDM : Flat, dark-energy & dark-matter dominated
- Primordial density fluctuations
  - Gaussian
- Set initial condition of underlying matter distribution using ΛCDM parameters





Galaxy Simulation Physics

- Dark matter (dissipation-less, collision-less)
  - Gravity-only
  - Particle N-body method

- Baryon / Gas evolution
  - Gravity + Hydrodynamics

- Add source & sink terms / sub-grid physics
  - Radiative cooling and heating of gas
  - Star formation and stellar feedback
  - AGN Accretion & Feedback

- Numerically integrate dynamical equations in comoving coordinates

Successful Results

- Hierarchical Structure Formation
  - Can reproduce the distribution and structure of galaxies in very large scales as seen in observations

- On small scales
  - Dynamical evolution of stars in star clusters

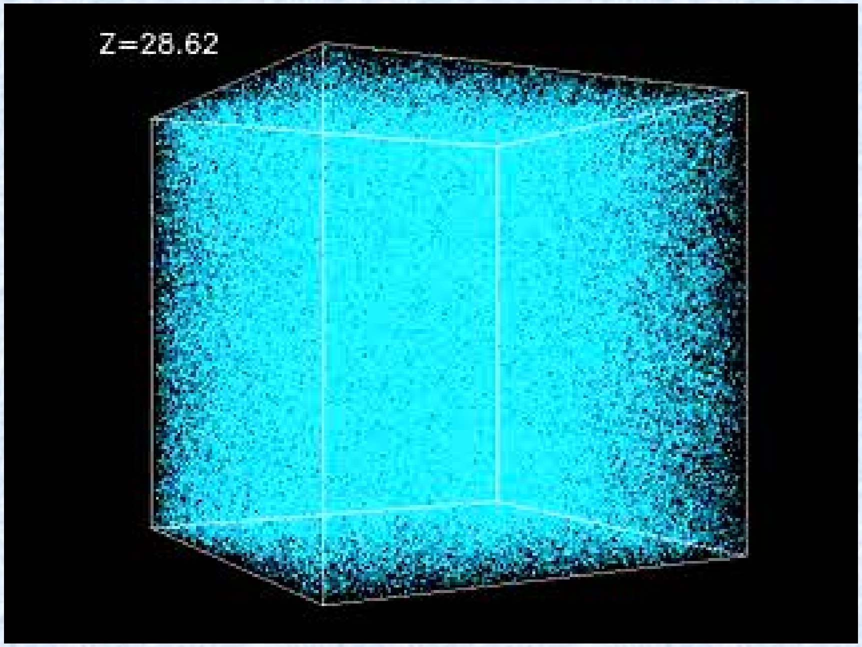
- Distribution of matter in the Universe
  - Collapse via gravitational forces into filaments. Galaxies form in these filaments

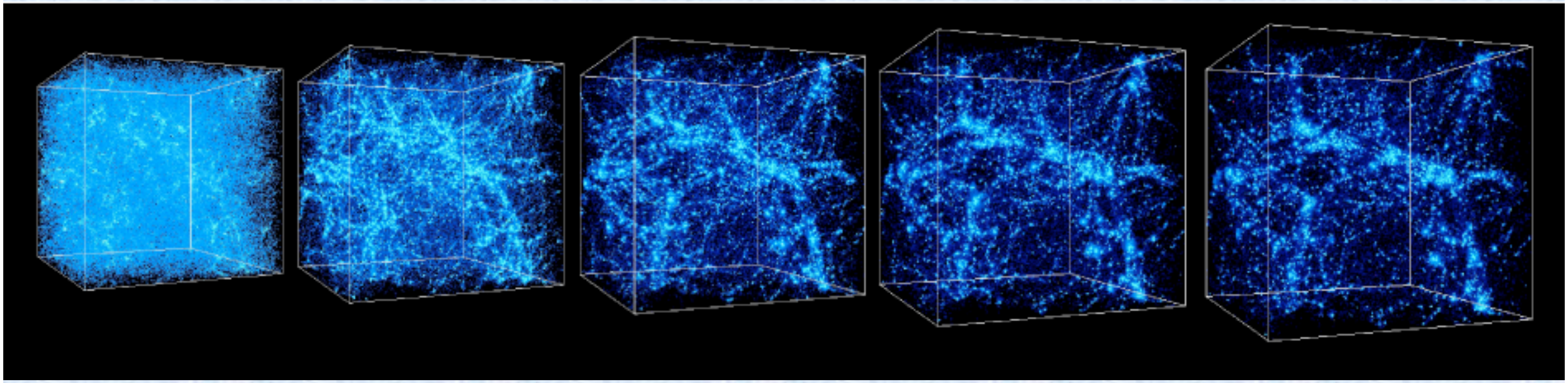
- Galaxy clustering at all z (z~0, z~1, z~4-5) observed in large scale surveys is well reproduced

Large-Scale Filaments

- A (43 Mpc)^3 box
- From $z = 30$ to $z = 0$

- Frames below show structure forming from $z = 10$ to the present

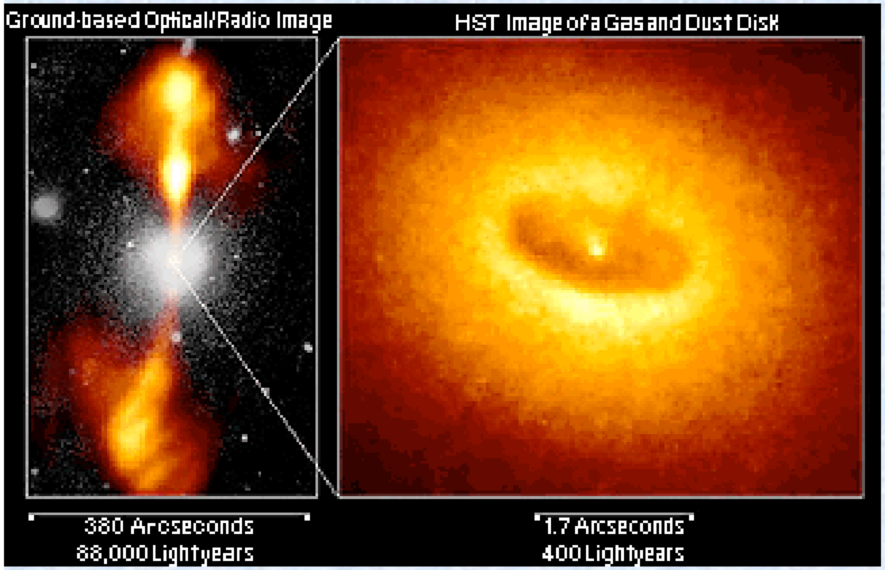




My work with Hugo Martel & Joël Germain :

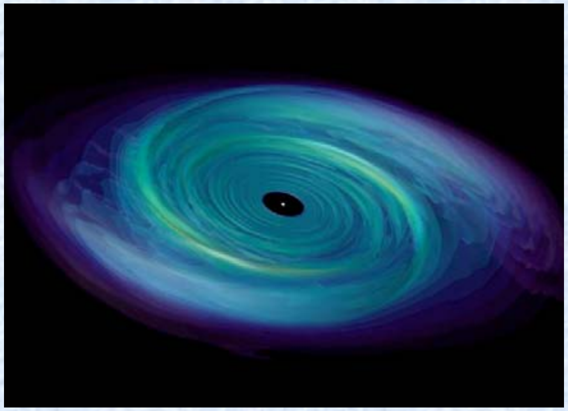
AGN Outflows in a Cosmological Volume

What is AGN?



- Active nucleus $\Rightarrow$ Central region radiates more energy than all the stars in the whole galaxy

- Very high luminosity (10^{44} - 10^{46} erg s^{-1})



- Powered by gas accretion onto a supermassive black hole (SMBH)
  - $M_{BH} > 10^6 M_{sun}$
  - Efficient conversion of mass into energy

How do AGN affect the Large-Scale Environment (InterGalactic Medium - IGM)?

- Radiated energy is fed back & coupled to the surroundings

- Mechanical outflow

- Goal : Investigate Metal enrichment of the IGM - Volume fraction, Metallicity

Cosmological Simulation

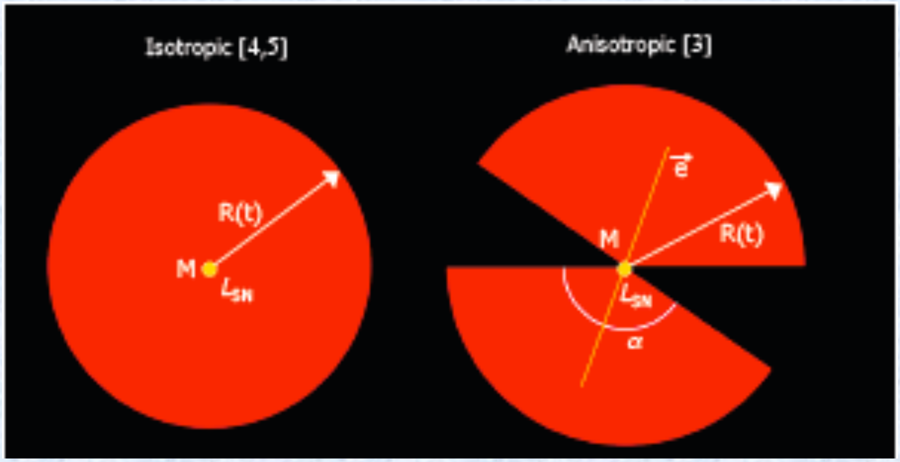
- N-body simulations of a cosmological volume
- P^3M (particle-particle/particle-mesh) code

- Box size (comoving) = 128 h^{-1} Mpc
- 256^3 particles, 512^3 grid
- Evolve from $z = 25$ up to $z = 0$
- ΛCDM model (WMAP5)

- Assume: baryonic gas distribution follows total matter in the simulation box
- Locate AGN at local density peaks within volume

Outflow Geometry

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



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

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

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

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 :

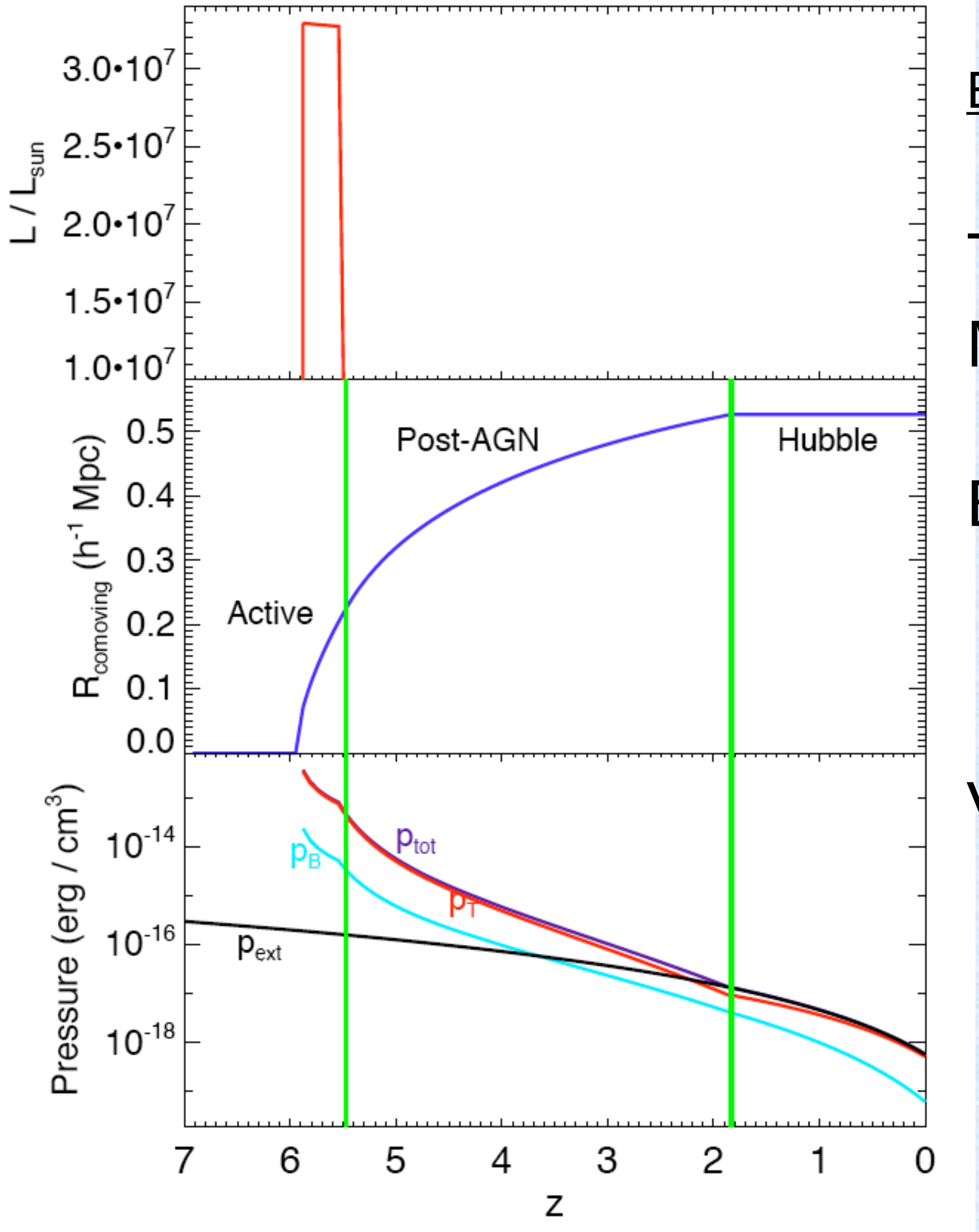
$$\dot{p}_T = \frac{\Lambda}{2\pi R^3\left[1-\cos(\alpha/2)\right]} - 5\, p_T \frac{\dot{R}}{R}$$

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

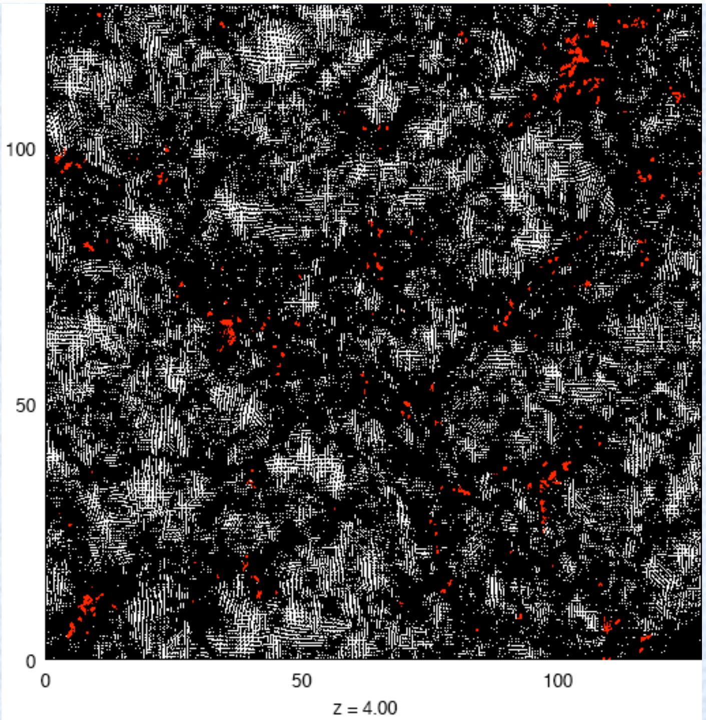
- Top: total luminosity.
- Middle: Comoving radius.
- Bottom: Pressures (external IGM, magnetic, thermal and total outflow).
- Vertical green lines separate phases of expansion: active, post-AGN and Hubble.

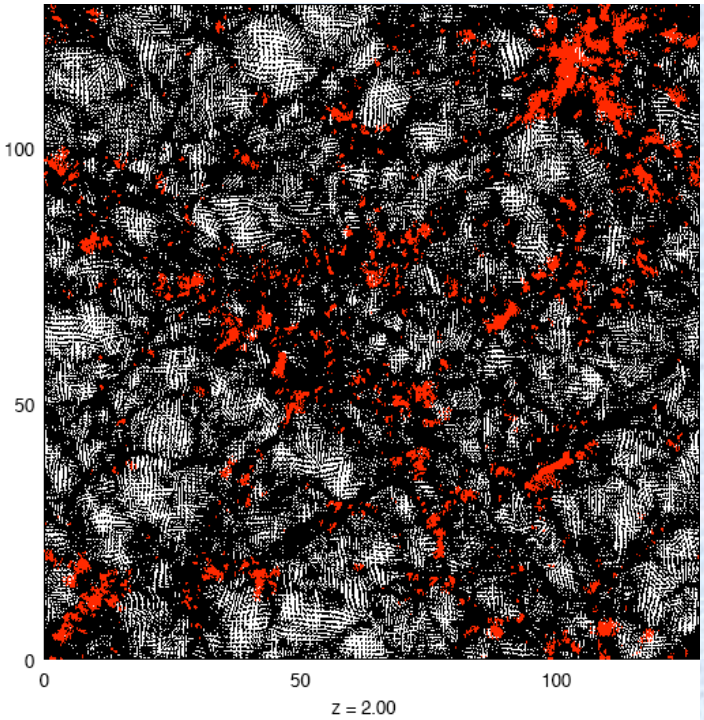
Metal Enrichment

- AGN outflows carry the metals produced by their host galaxies, & deposit those to the surrounding IGM volume

- 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

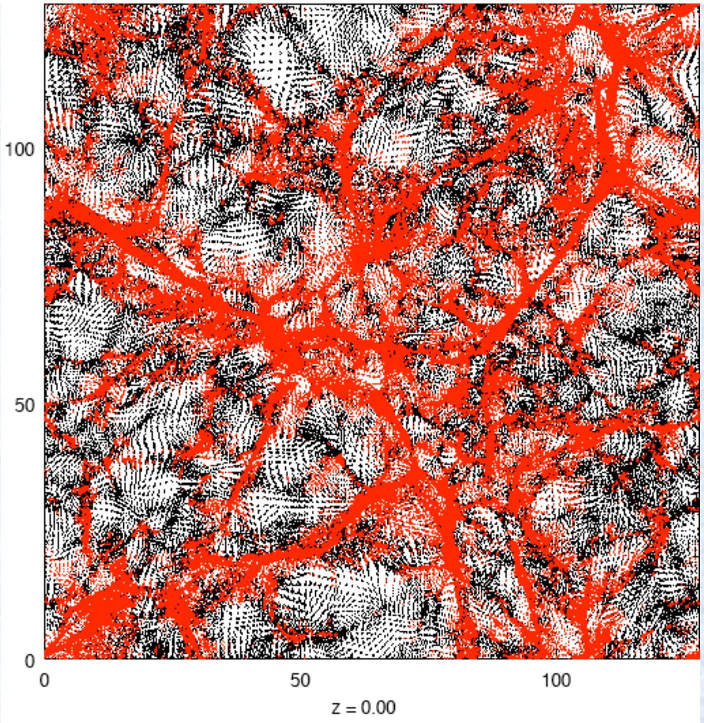


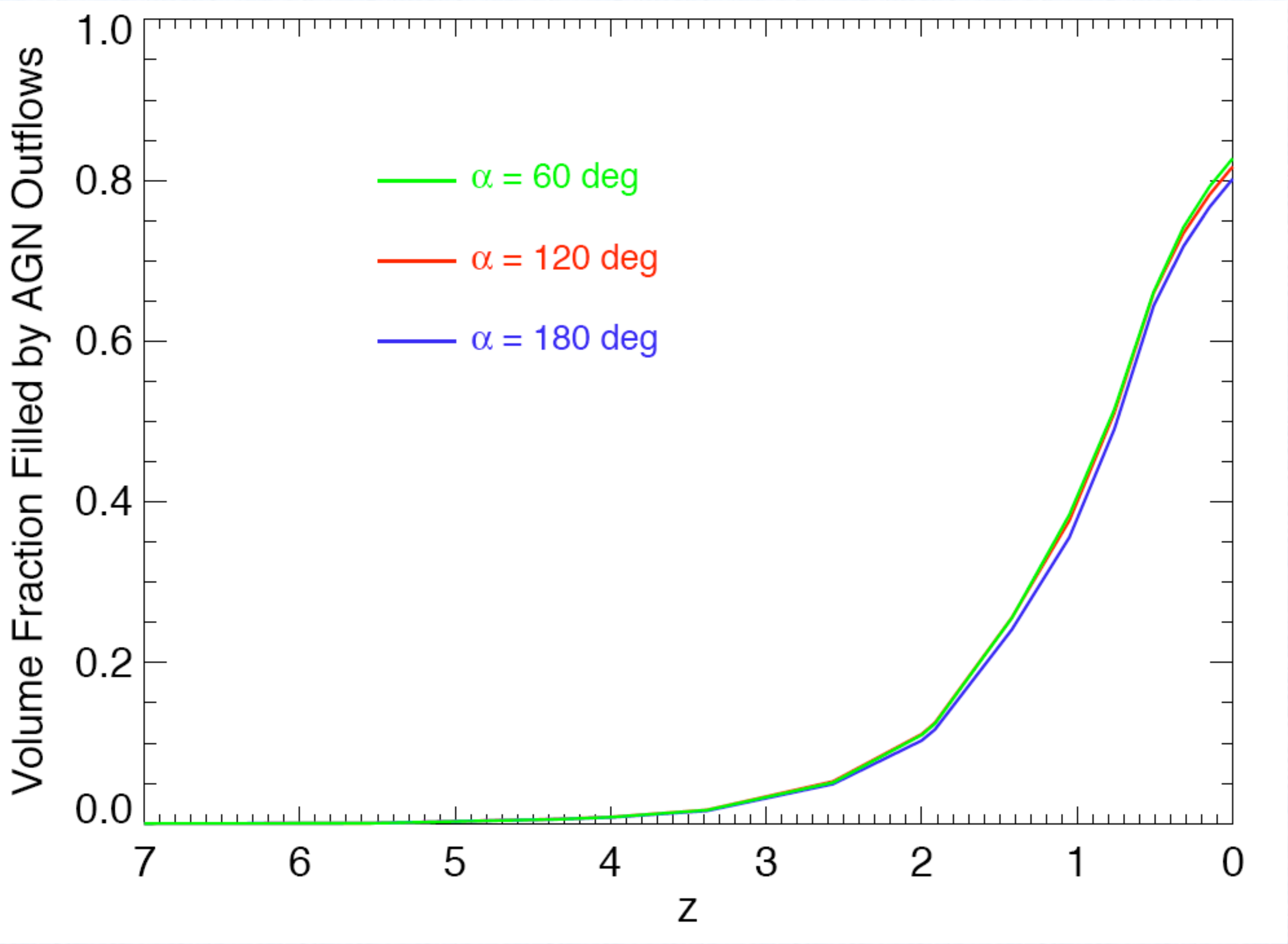


A slice of the box (128/h Mpc × 128/h Mpc × 4/h Mpc) at different redshifts.

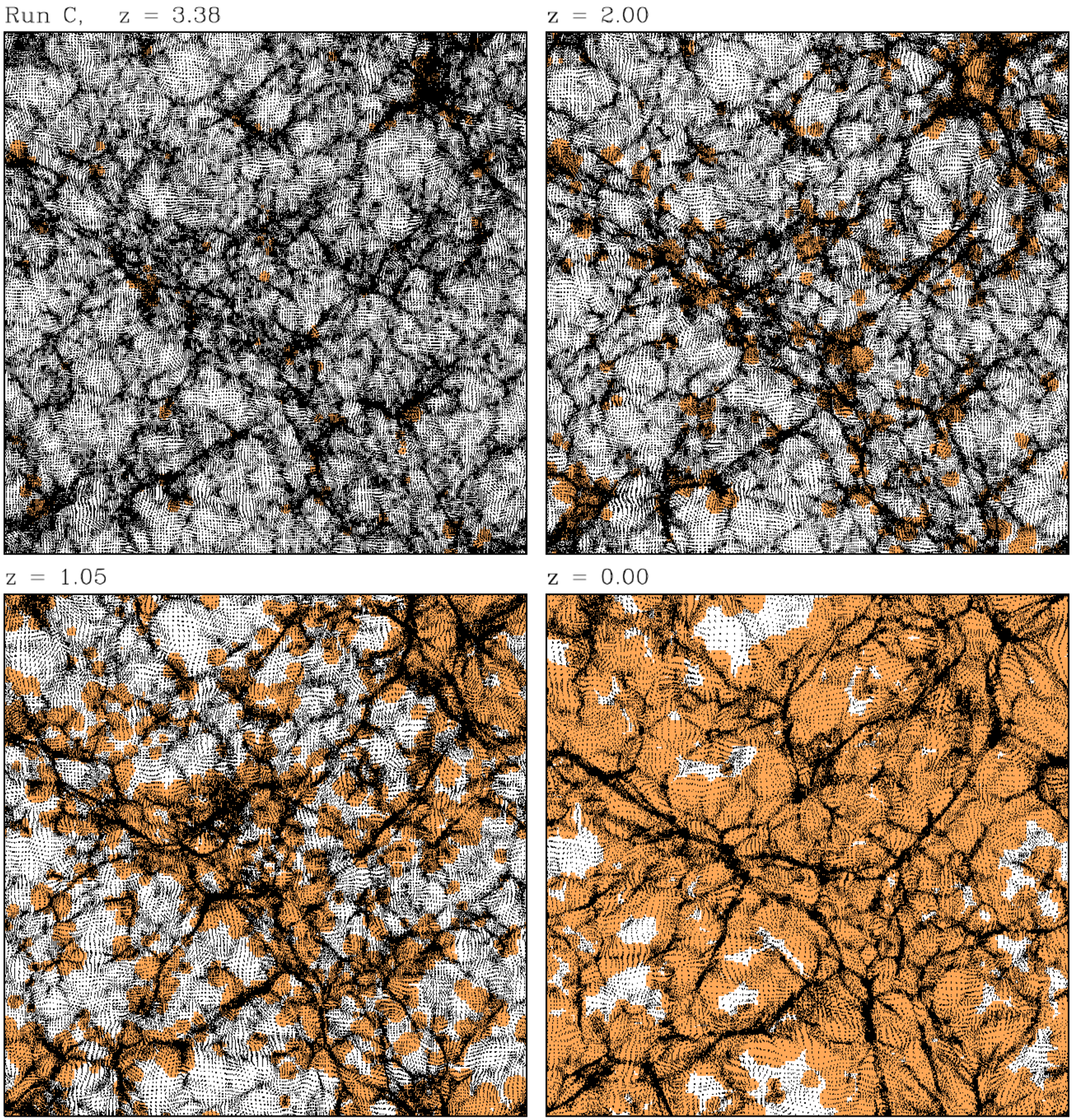
Black dots: Non-enriched particles.

Red dots: Enriched particles.





Volume fractions enriched (for different opening angles)



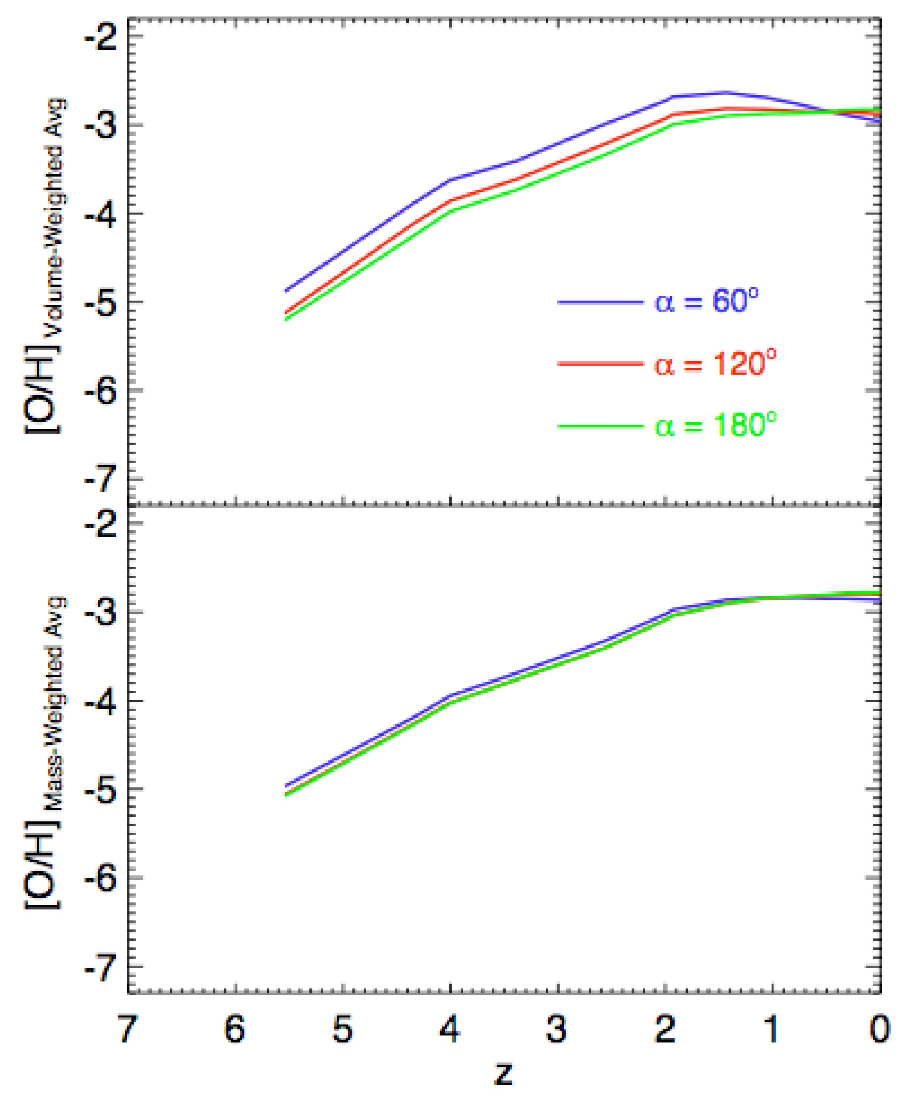
Evolution of metal distribution in a slice

(128/h Mpc × 128/h Mpc × 2/h Mpc).

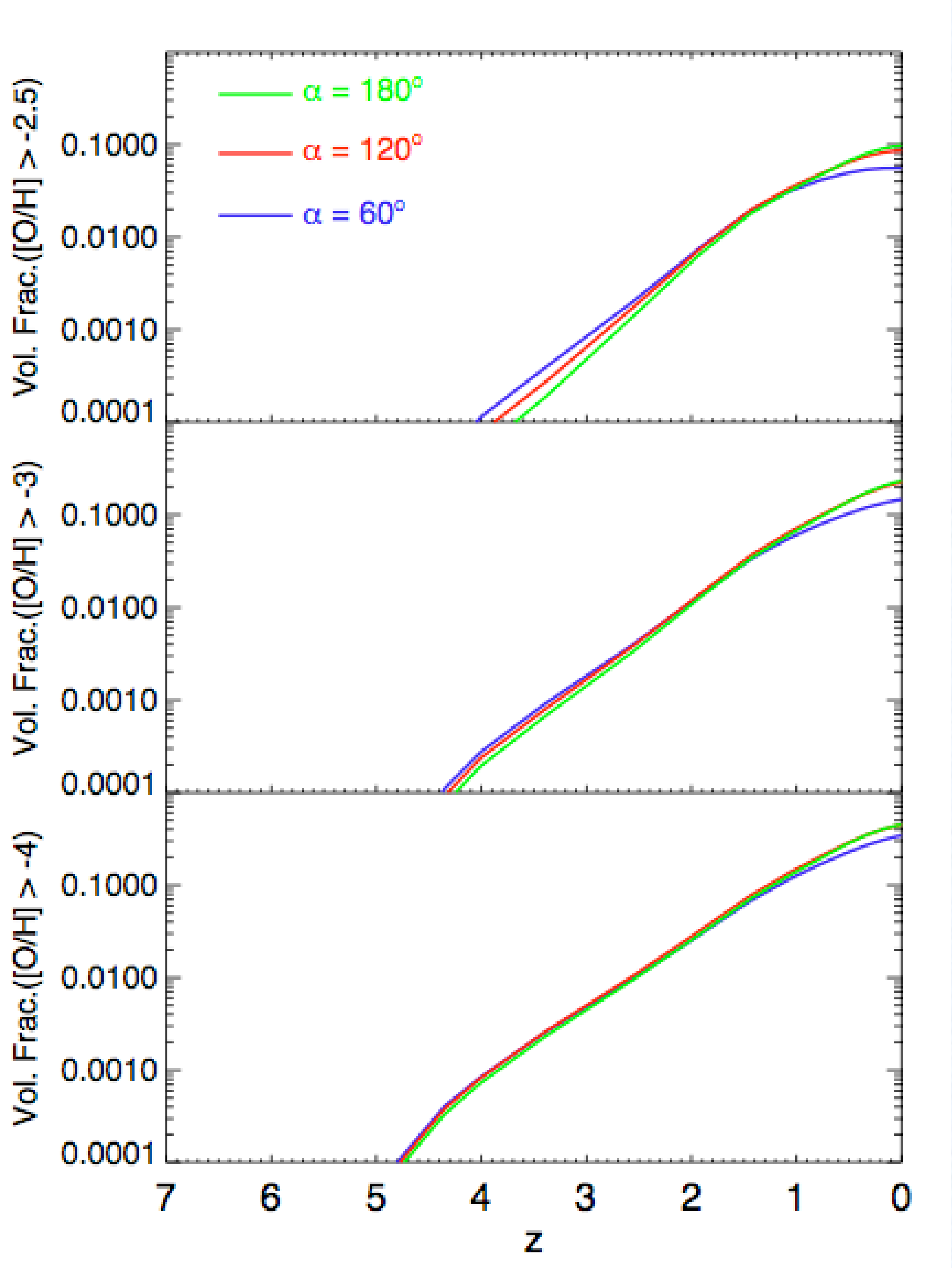
Orange : enriched volumes.

Black dots : P^3M particles, showing the large-scale structures.

$\alpha = 60°$



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.



Enriched 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,

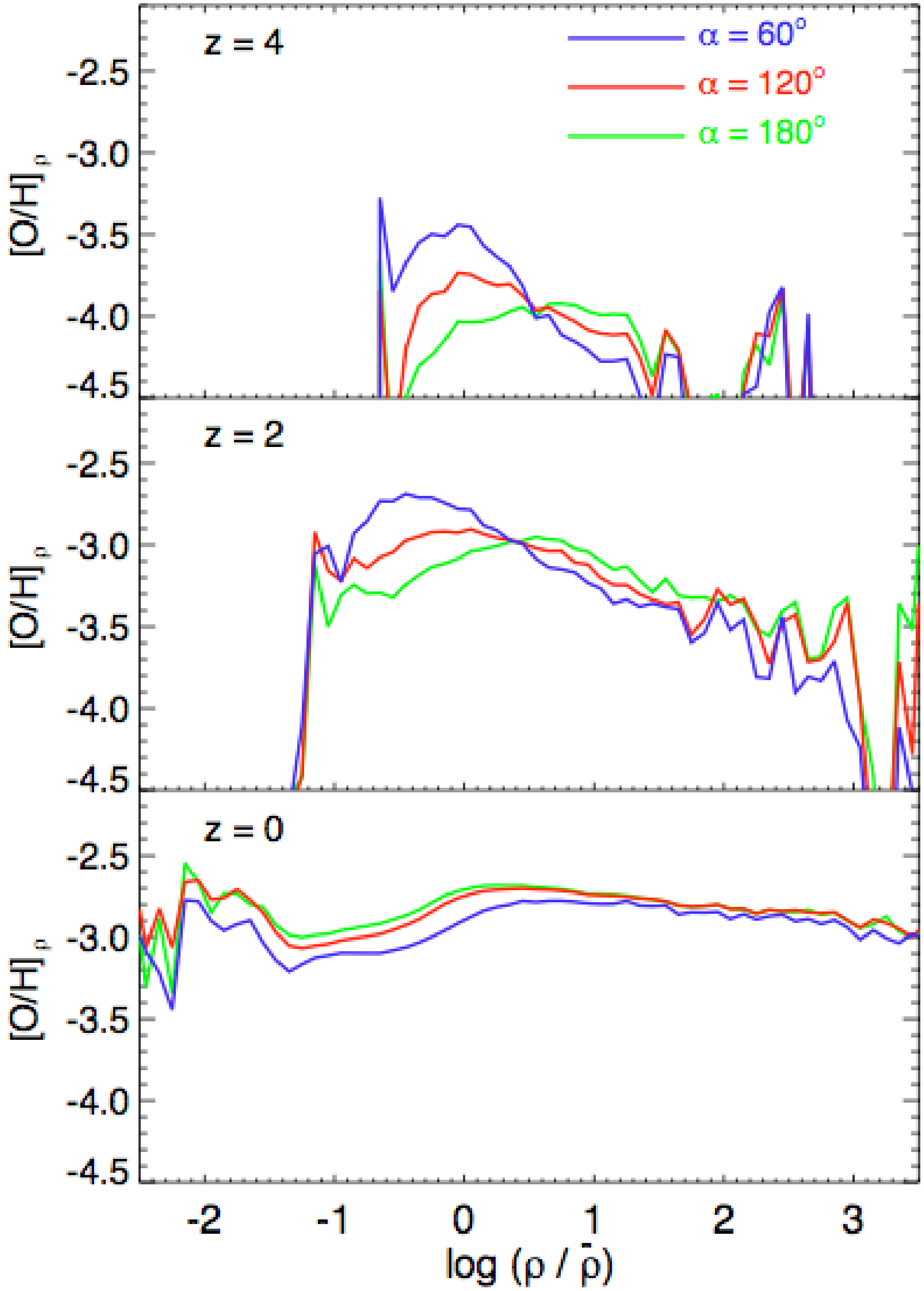
14−24% volume to [O/H] > −3,

34−45% volume to [O/H] > −4.

Contribution to the IGM Metallicity

$$\begin{aligned} Z_{IGM} &\sim 10^{-4} Z_{\mathrm{Sun}}, \text{ at } z = 5 \\ &\geq 10^{-3} - 10^{-2} Z_{\mathrm{Sun}}, \text{ at } z \sim 2 - 3 \\ &\geq 10^{-2} - 10^{-1} Z_{\mathrm{Sun}}, \text{ at low} - z \end{aligned}$$

- CIV and OVI observations
  - Songaila (2001, ApJ, 561, L153)
  - Simcoe, Sargent & Rauch (2004, ApJ, 606, 92)
- Propagation of metals by AGN outflows do not account for 100% of the observed IGM metals
  - They only contribute a fraction
- Need to count metals ejected by outflows driven by SNe or starbursts, from dwarf & low-mass galaxies, at high-z (6 < z < 15)
  - Scannapieco, Ferrara & Madau (2002, ApJ, 574, 590)
  - Oppenheimer & Dave (2006, MNRAS, 373, 1265)



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

Initially, more anisotropic outflows preferentially enrich low-density regions,

but this trend gets eventually washed-out as the enriched volume fraction approaches unity.

Summary & Conclusions

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

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

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

- IGM is metal-enriched to ~ 10 - 20 % of the observed metallicity, the result depending on redshift

- Increasingly anisotropic outflows preferentially enrich under-dense regions, esp. at higher redshifts
  - Can explain observations of enriched low-density IGM at $z \sim 3 - 4$

References

- Barai, P., Martel, H. & Germain, J. 2011, ApJ, 727, 54
- Germain, J., Barai, P. & Martel, H. 2009, ApJ, 704, 1002
- Martel, H. & Shapiro, P.R. 2001, RevMexAA, 10, 101
- Pieri, M. M., Martel, H. & Grenon, C. 2007, ApJ, 658, 36

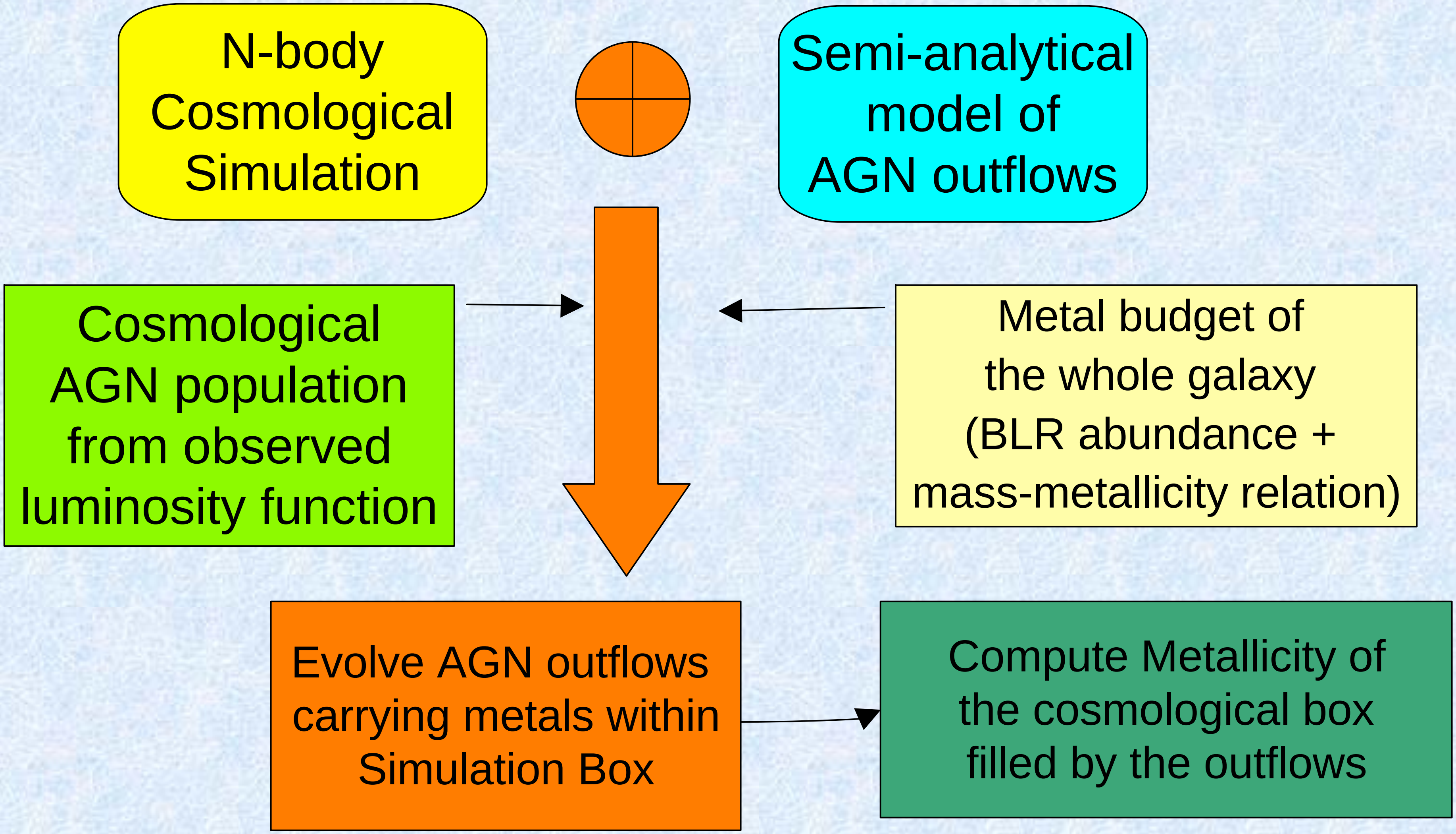
Extra Slides

Simulation Volume

- The computational box has Hubble expansion just like the real Universe
  - Always encompasses the same mass

- The expansion is taken out from computations, s.t. the box appears static
- Coordinate system that expands (or co-moves) with the Universe (the comoving coordinates) is used

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

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, $T_{\mathrm{AGN}} = 10^8$ yr,

  Total number of sources from QLF = 1,535,362

- Locate AGN at local density peaks within simulation box

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

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

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

Ambient Medium for AGN Outflows

- Assume: baryonic gas distribution follows dark matter in the simulation box
- 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 : $\mu = 0.611 \text{ a.m.u.}$

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

  $= N_{AGN} / N_{ff}^3$

Compute Metallicity: Mass of Metals in Galaxy

- Metals generated in galaxies are transported to the IGM
- 2 regions of stellar populations:

1) Near the AGN (central regions) $M_{Z,1} = \left(5Z_{\text{Sun}}\right)M_{BH}$
2) Away from central AGN (within rest of the galaxy)

$$M_{Z,2} = f_{esc}Z_G\left(1 - f_*\right)M_{gal}$$

  - Redshift-dependent mass-metallicity relation (Maiolino et al. 2008, A&A, 488, 463)

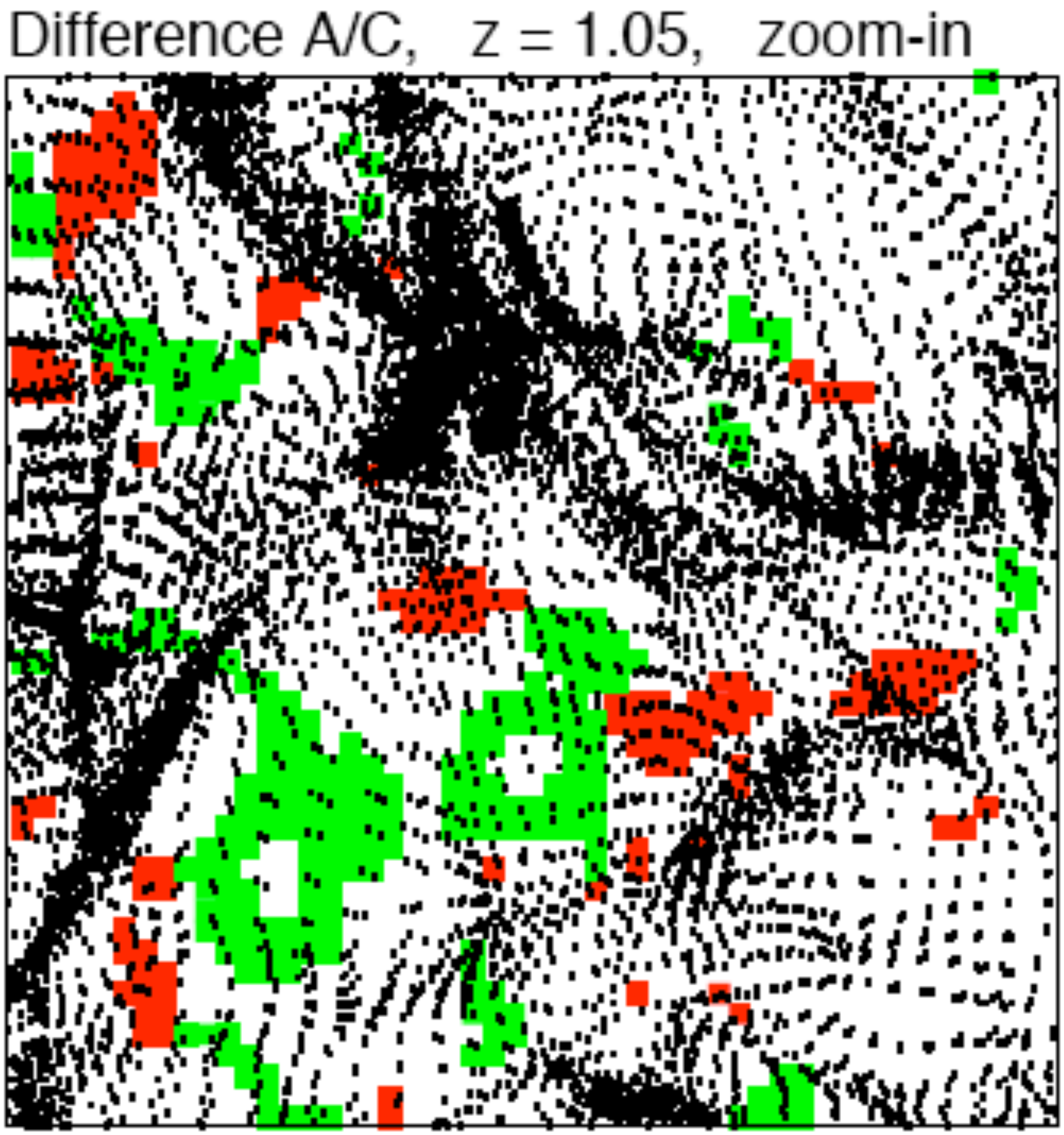
$$12 + \log\left(\frac{O}{H}\right) = -0.0864\left(\log M_* - \log M_0\right)^2 + K_0$$

Distribution of Metals from Galaxy to IGM

- Total mass of metals carried is deposited uniformly into the IGM gas overlapped by the outflow

$$\boxed{M_{Z,out} = M_{Z,1} + M_{Z,2}}$$

- All the metals are added to the IGM by the active lifetime
- Metals are redistributed (conserving total metal mass, using an averaging technique) to the larger volumes overlapped in the post-AGN overpressured expansion, until the outflow reaches the passive Hubble flow evolution



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 = 1.05

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