Metal Enrichment of the Circum-Galactic Medium around Massive Galaxies at Redshift 3

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How do metals in the CGM (and the IGM) get there?

- There are metals out there in the CGM & IGM (e.g., Cowie & Songaila 1998; Schaye et al. 2003; Adelberger et al. 2003, 2005; Aguirre et al. 2008; Danforth & Shull 2008; Simcoe et al. 2011);
  - Association of metal absorbers and galaxies (e.g., Adelberger et al. 2003, 2005; Bordoloi et al. 2011)
  - Metals are there since high redshift -- Ω(C IV), Ω(Si IV) remain approx. constant since z ~ 4.5 (e.g., Ryan-Weber et al. 2009; Cooksey et al. 2010, 2011)

Large-scale Galactic winds

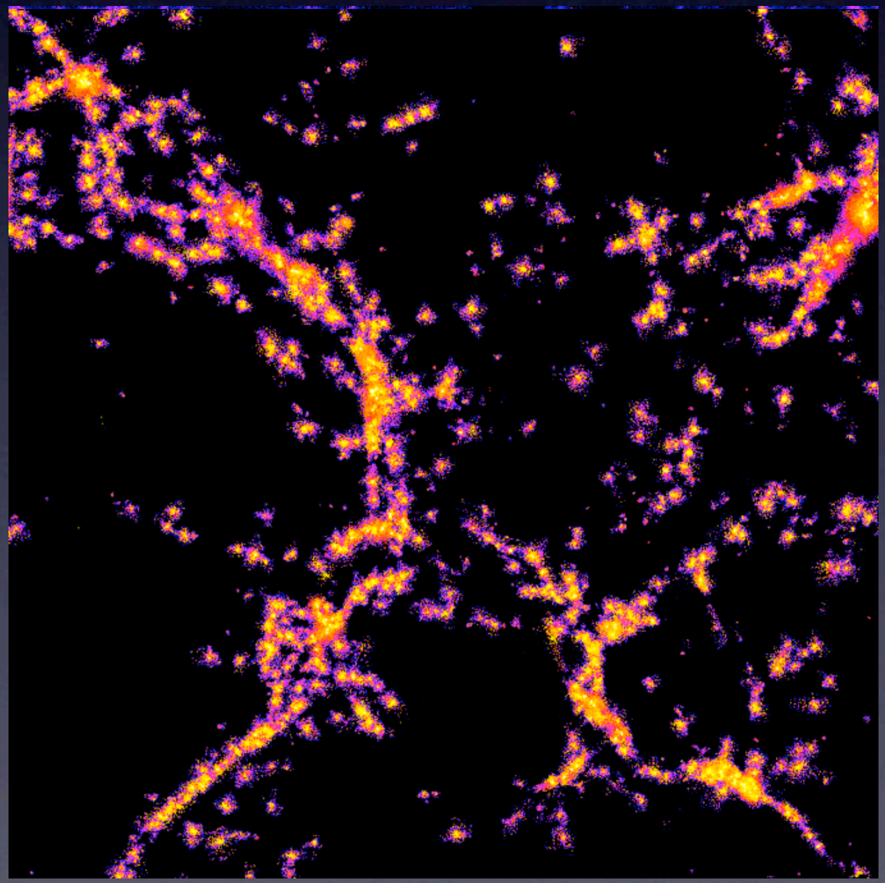
- Galactic-scale outflows observed in high-z galaxies and local starburst galaxies (e.g., Pettini et al. 2001; Martin 2005; Weiner et al. 2009; Steidel et al. 2010)

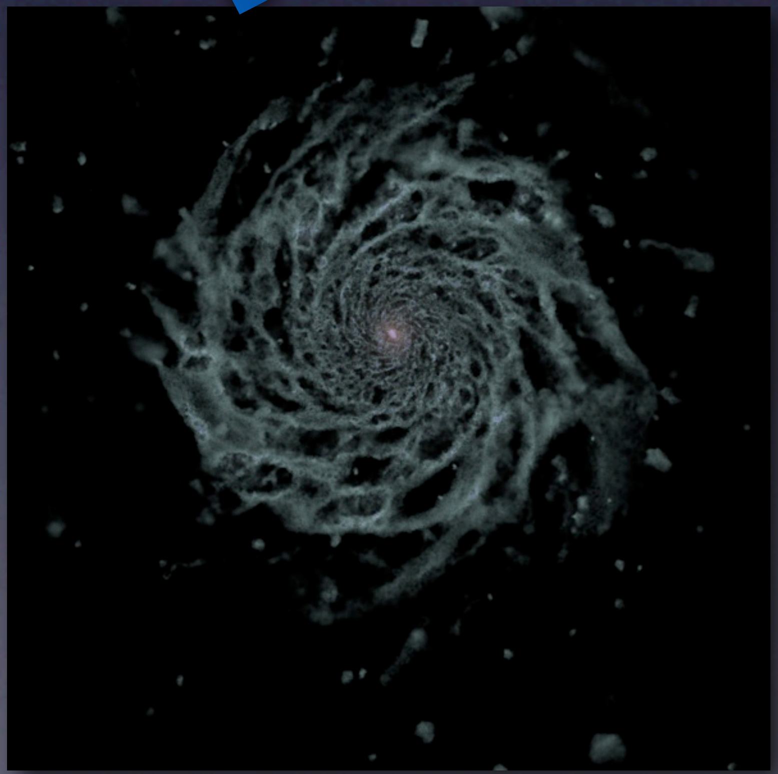
Early outflows from dwarfs

- When were metal produced? How are metals transported by outflows? how far do they travel?

Simulations: Cosmological Volume vs. Zoom-in Galaxies

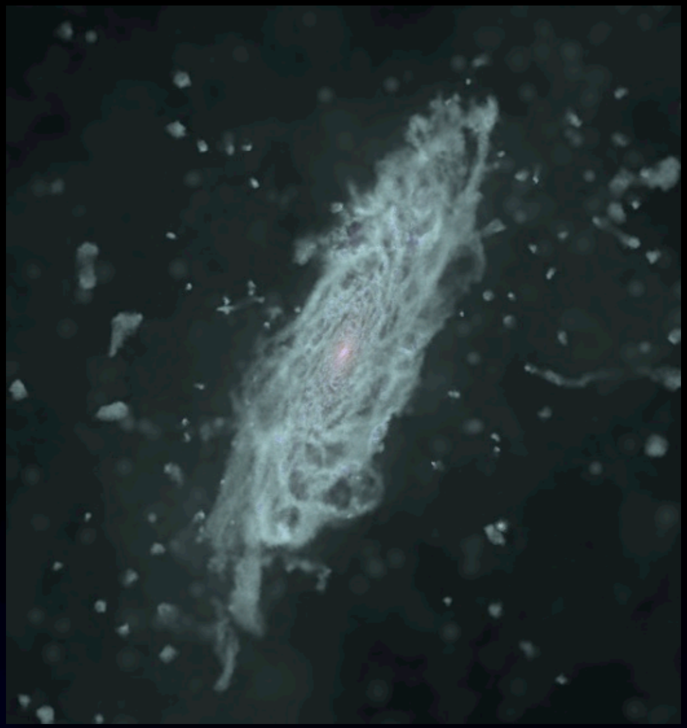
- Hydrodynamical simulations cosmological volumes (e.g., Aguirre et al. 2005; Oppenheimer & Dave 2006, 2008; Wiersma et al. 2009; Cen et al. 2010; Shen et al. 2010; Smith et al. 2010)





Pros: large sample of galaxies, good statistics
Cons: Lower Resolution -- limited ability to follow early enrichment and transportation of metals

The 'Eris' Simulation



Guedes et al. 2011, arXiv:1103.6030

The soldiers fought like wolves while Eris, the Lady of Sorrow, watched with pleasure.
-- The Iliad

- TreeSPH code Gasoline (Wadsley et al. 2004)
- SF: $d\rho_*/dt = \varepsilon_{SF}\rho_{gas}/t_{dyn} \propto \rho_{gas}^{1.5}$ when gas has $n_H > n_{SF}$
- Blastwave feedback model for SN II (Stinson et al. 2006): radiative cooling prohibited for the super-bubble expansion phase (McKee & Ostriker 1977)
- Metals produced self-consistently from SN Ia and SN II following yields from Woosley & Weaver (1995)

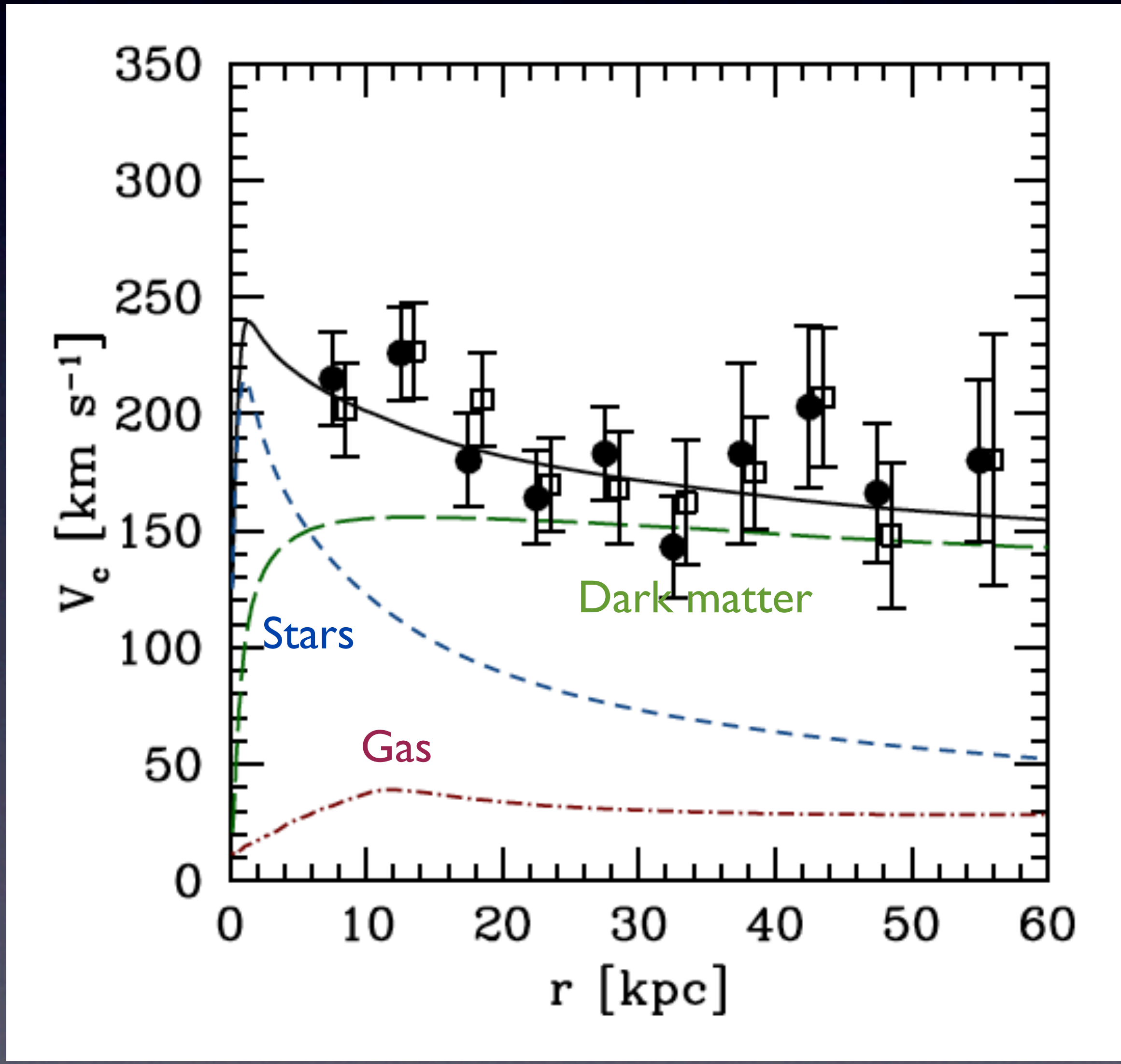
Galaxy	m_{DM} (Ms)	m_{SPH} (Ms)	ε_G (pc)	n_{SF} (cm^{-3})
Eris	9.8×10^4	2×10^4	120	5.0

Very high resolution - 18.6 M particles within Rvir, to resolve the galaxy structure, its progenitors and companions

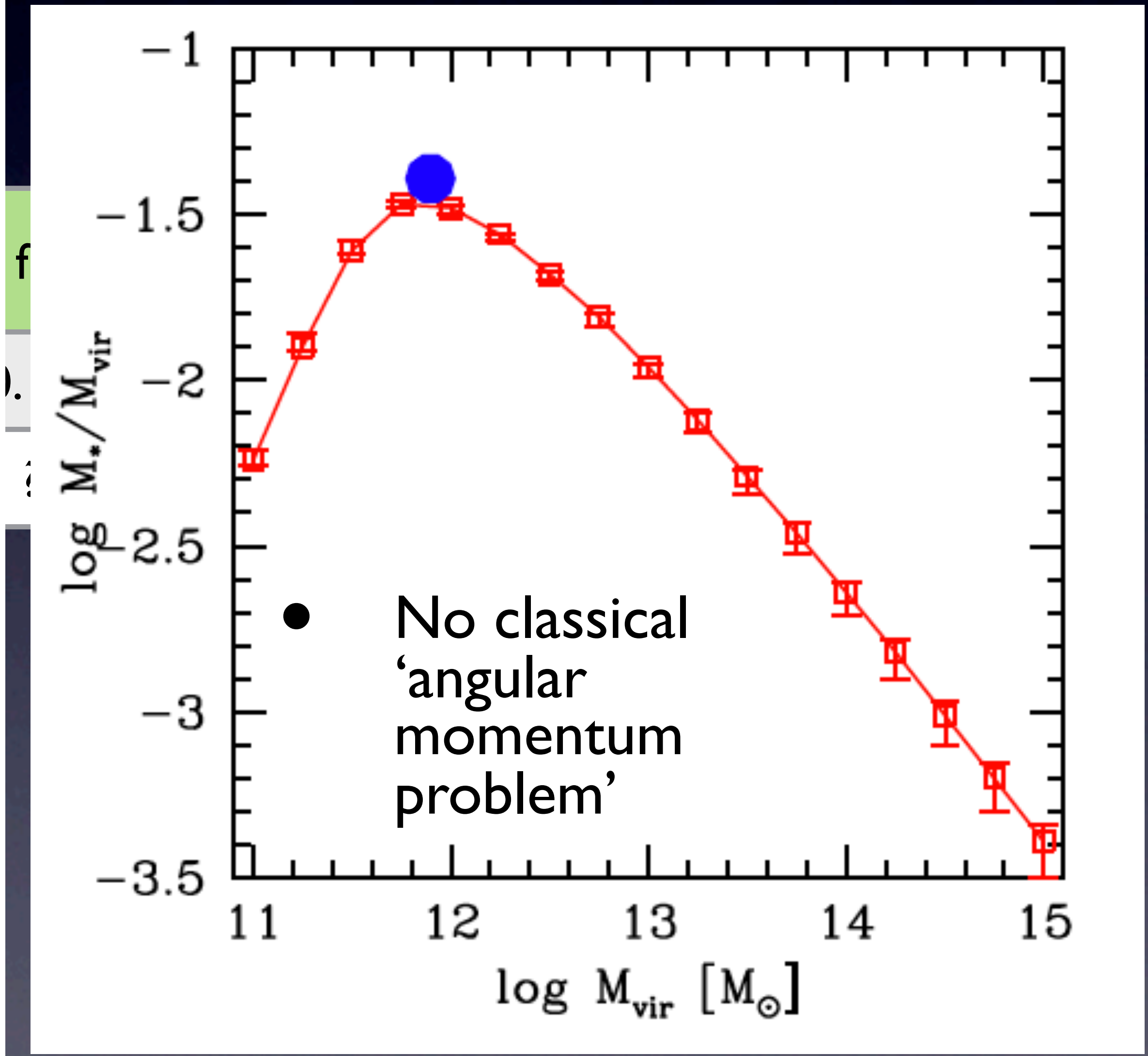
High SF threshold, allow the inhomogeneous SF site to be resolved and localize feedback

Eris: General Properties at the Current Epoch

- At z = 0, a close analog of the Milky Way Galaxy (Guedes et al. 2011)



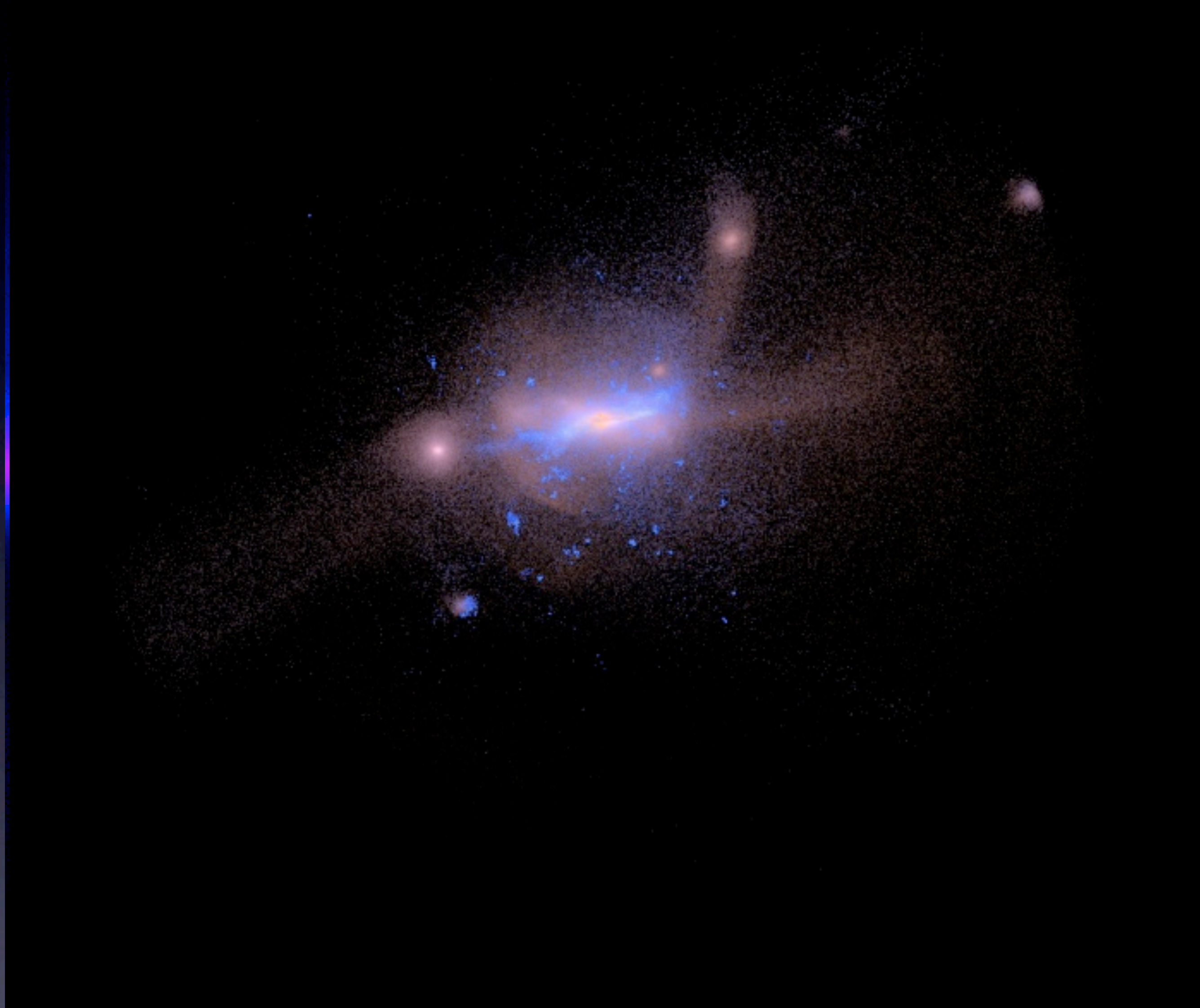
Data points from Xue et al. 2008

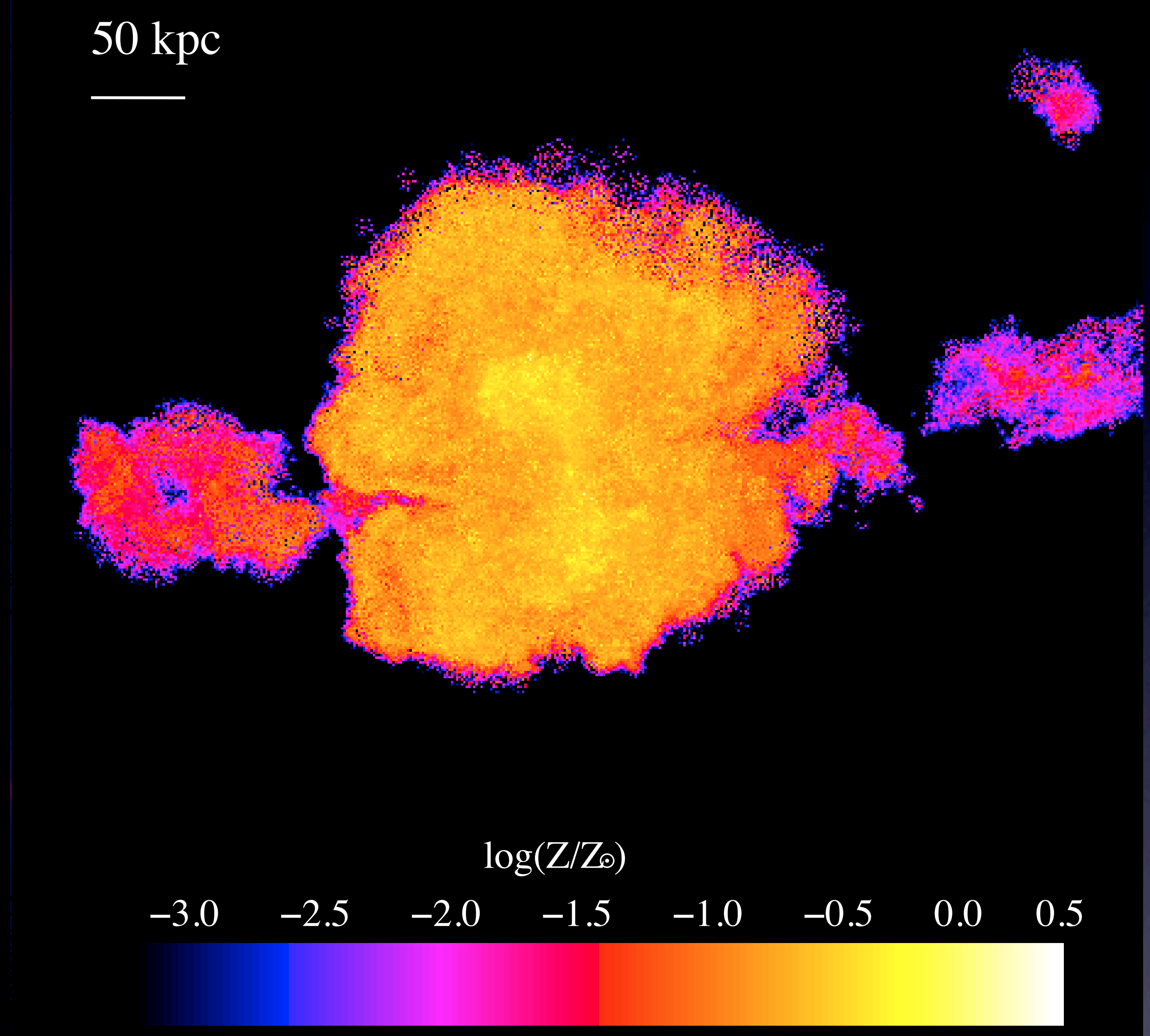


Observations from Behroozi et al. (2010)

Eris at Redshift z = 3

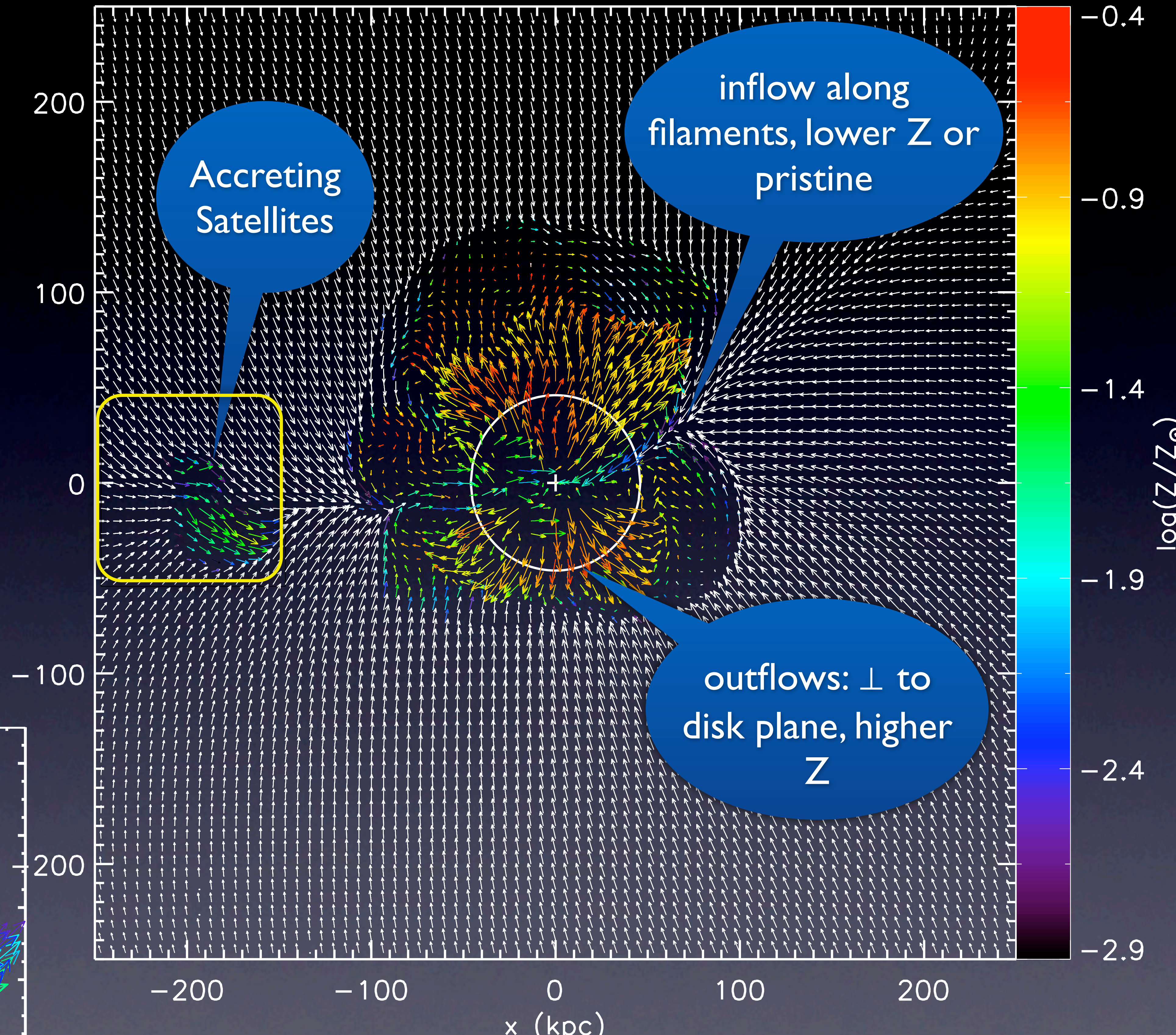
Rest-Frame B, U and NUV stellar composite of the Eris at z = 3, using SUNRISE (Jonsson 2006)

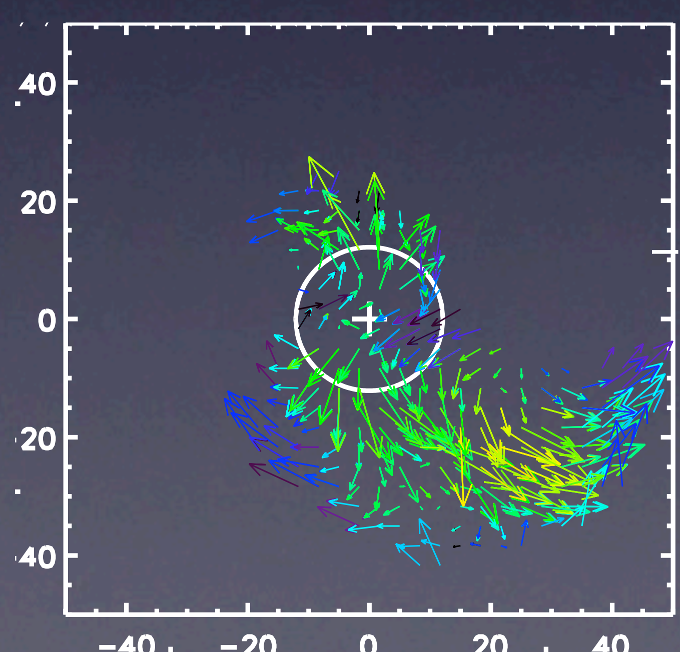




- Resemble a LBG; M_{vir} = 2.3 x 10^{11} M_{sun}; R_{vir} =46 kpc; Star formation rate about 9 M_{sun}/yr.
- Stellar mass 1.2 x 10^{10} M_{sun}. Metallicity of cold, SF gas [O/H] + 12 = 8.1 (-0.6 solar value), consistent with the M*-Z relationship at higher redshift (e.g., Mannucci et al. 2010)
- Metal distribution extends up to 250 kpc, ~5 x R_{vir}

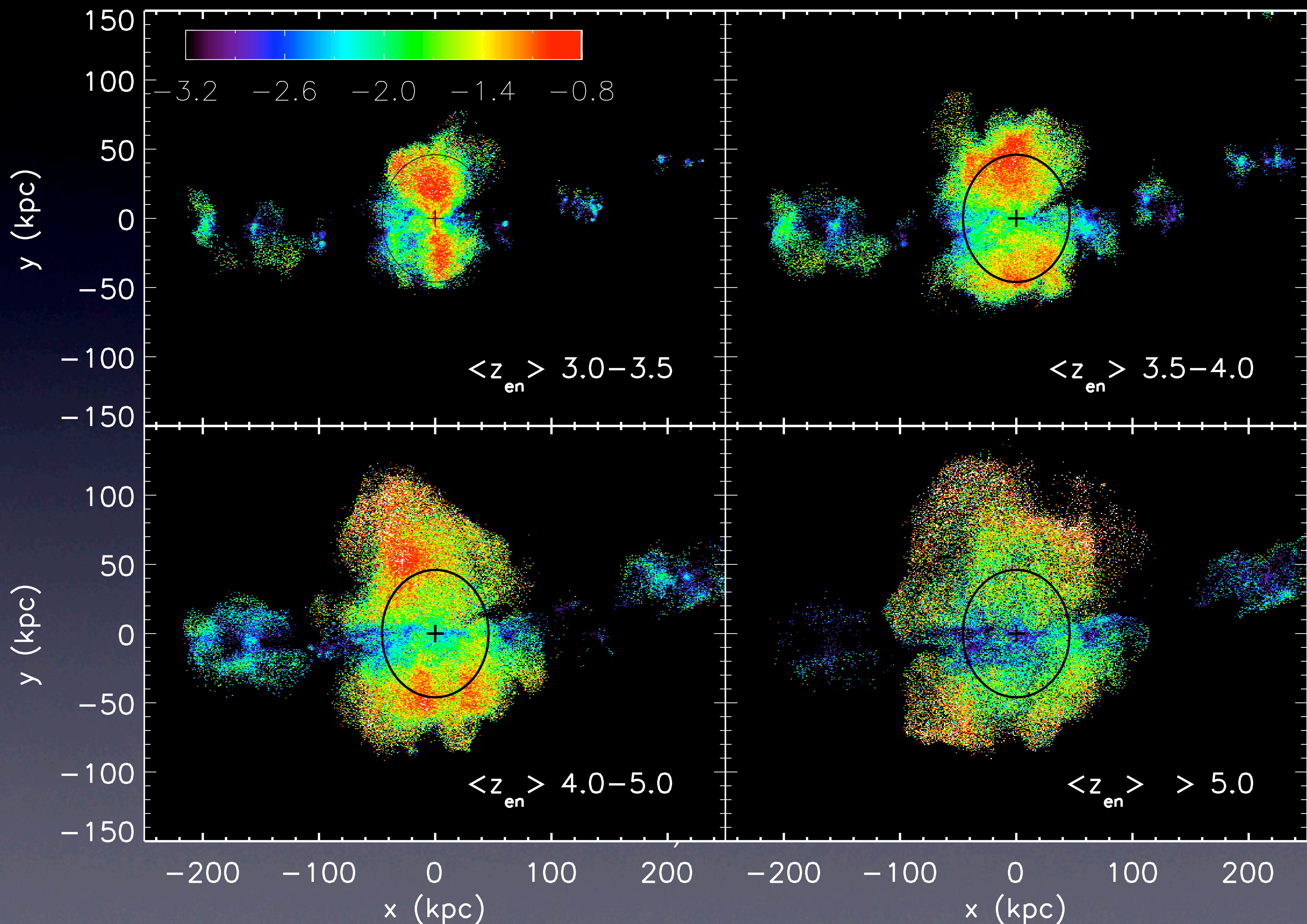
- 500 x 500 x 10 kpc slice, projected to x-y plane, disk edge-on
- Max projected averaged velocity ~224 km/s (host) and 106 km/s (satellite)





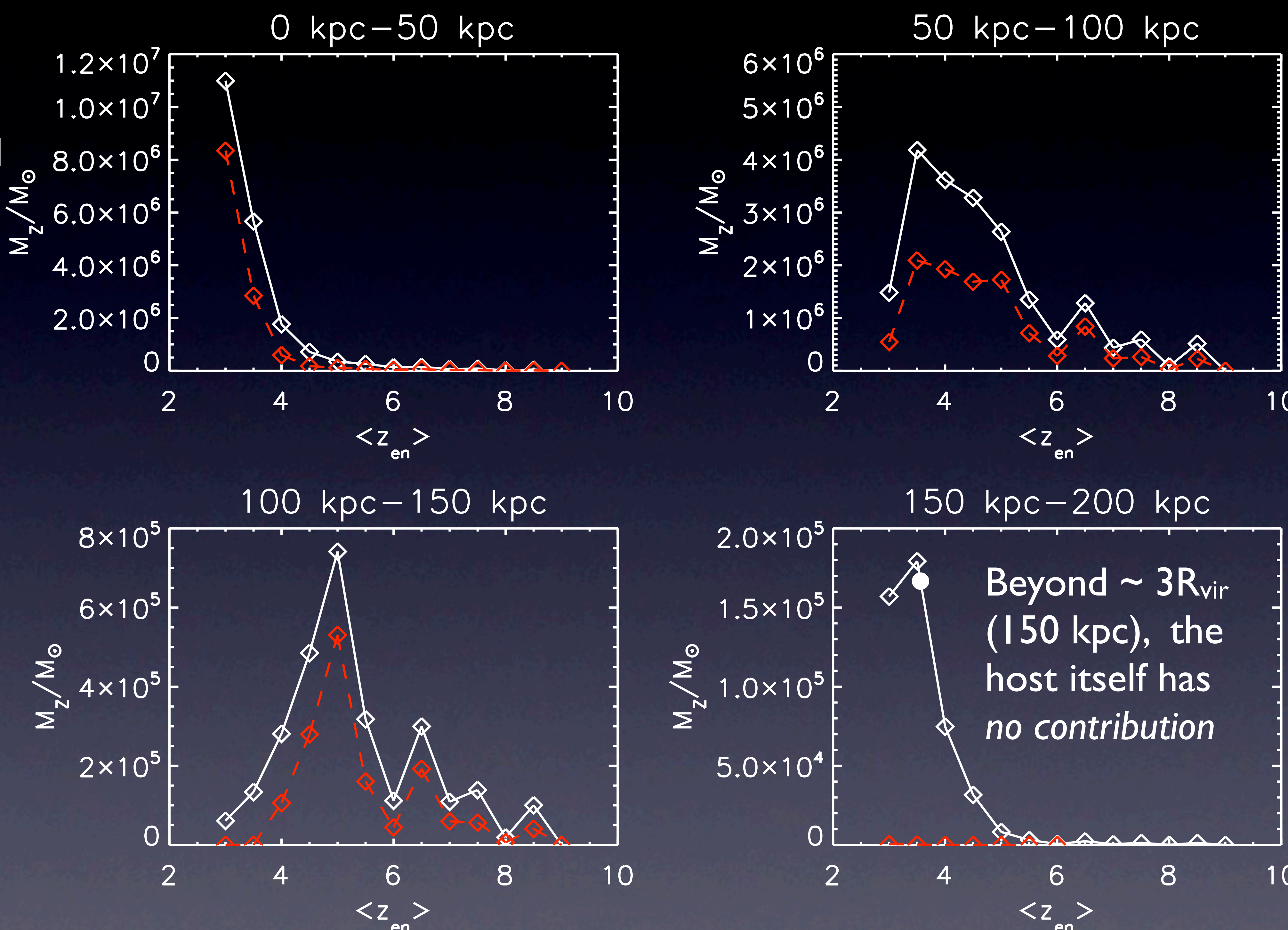
Shen et al. 2011, in prep.

When are the CGM metals produced?



Epochs of Metal Production

- Within 3 R_{vir}, both the host and its satellites contributes to the metal production

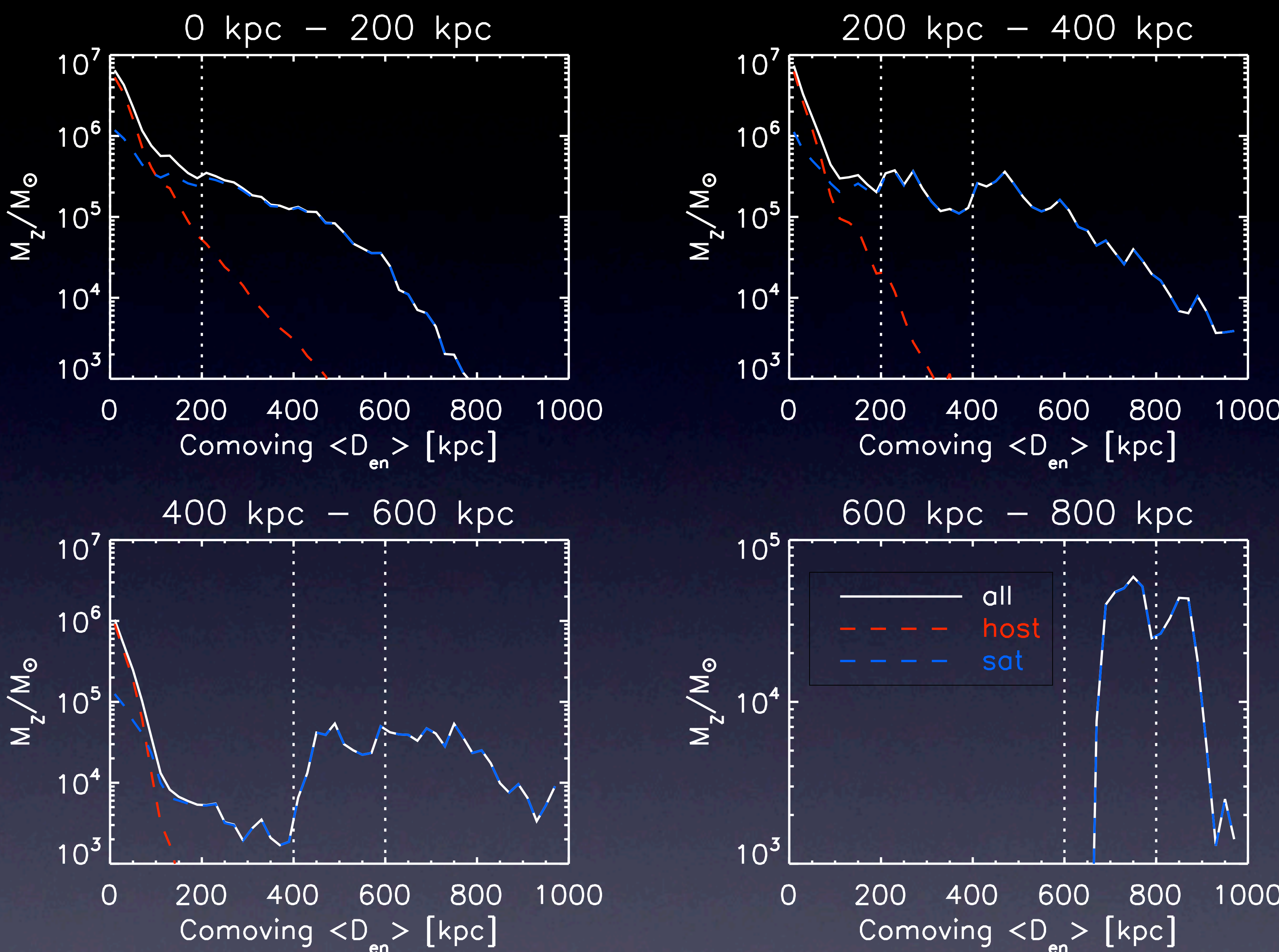


- Beyond 2 R_{vir}, early ($z > 5$) metal production starts to dominate -- about 14% of metals are from late ($z < 5$) superwinds.

The Journey of Metals: Inflow vs. Outflow?

Physical distance: 0-1 R_{vir}

Physical distance: ~1-2 R_{vir}

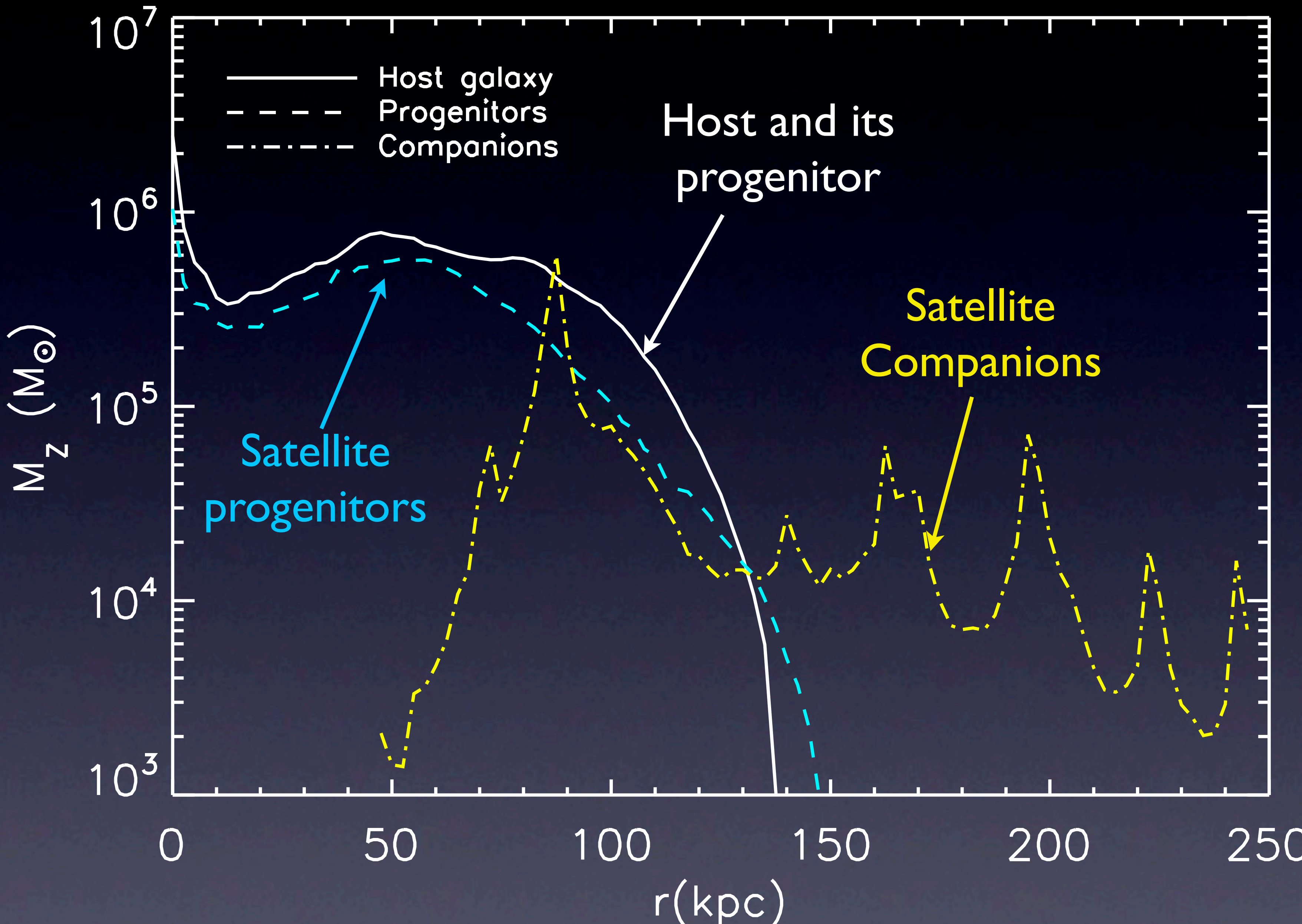


Physical distance: ~2-3 R_{vir}

Physical distance: ~3-4 R_{vir}

- Mean enrichment distance: $\langle D_{en} \rangle = \sum \Delta m_z^i \, d_{en}^i / \sum \Delta m_z$, comoving distance used
- Host metals: Most ejected from the central regions by galactic outflows
- Satellite metals: 30%-40% transported *inwards* from the enrichment site

Contribution of Host, Satellites Progenitors and Companions

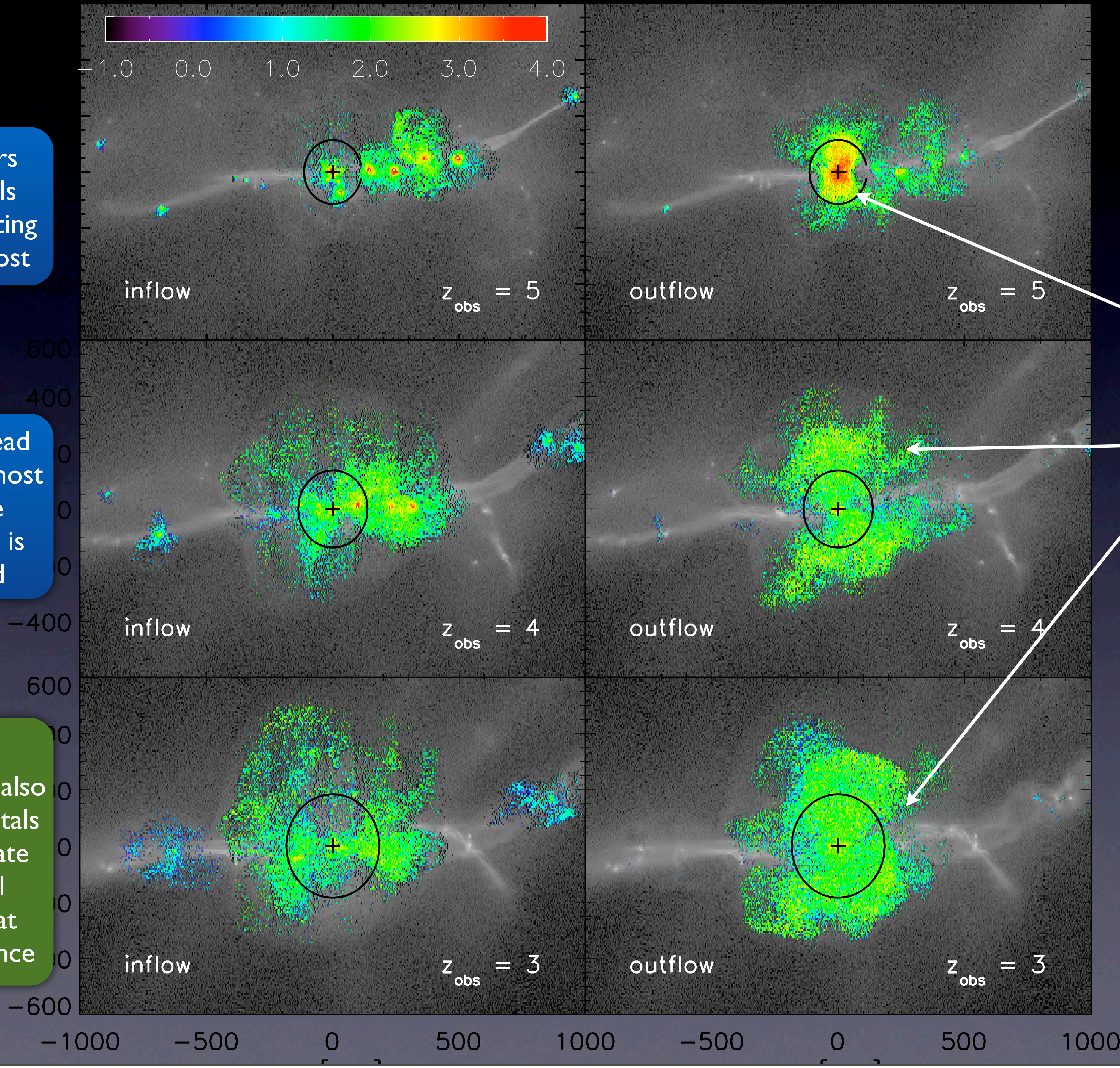


- Companions: Satellite has not accreted yet at z = 3
- Progenitors: satellite has accreted by z = 3

	r ≤ Rvir	r ≤ 2 Rvir	r ≤ 3 Rvir	r > 3 Rvir
Host	61%	58%	58%	0
Sat. Progenitors	39%	38%	37%	3%
Sat. Companions	0	4%	5%	97%

Contribution from Satellites

- Spatial evolution of metals produced at $7 < z \leq 5$ in *satellite only*



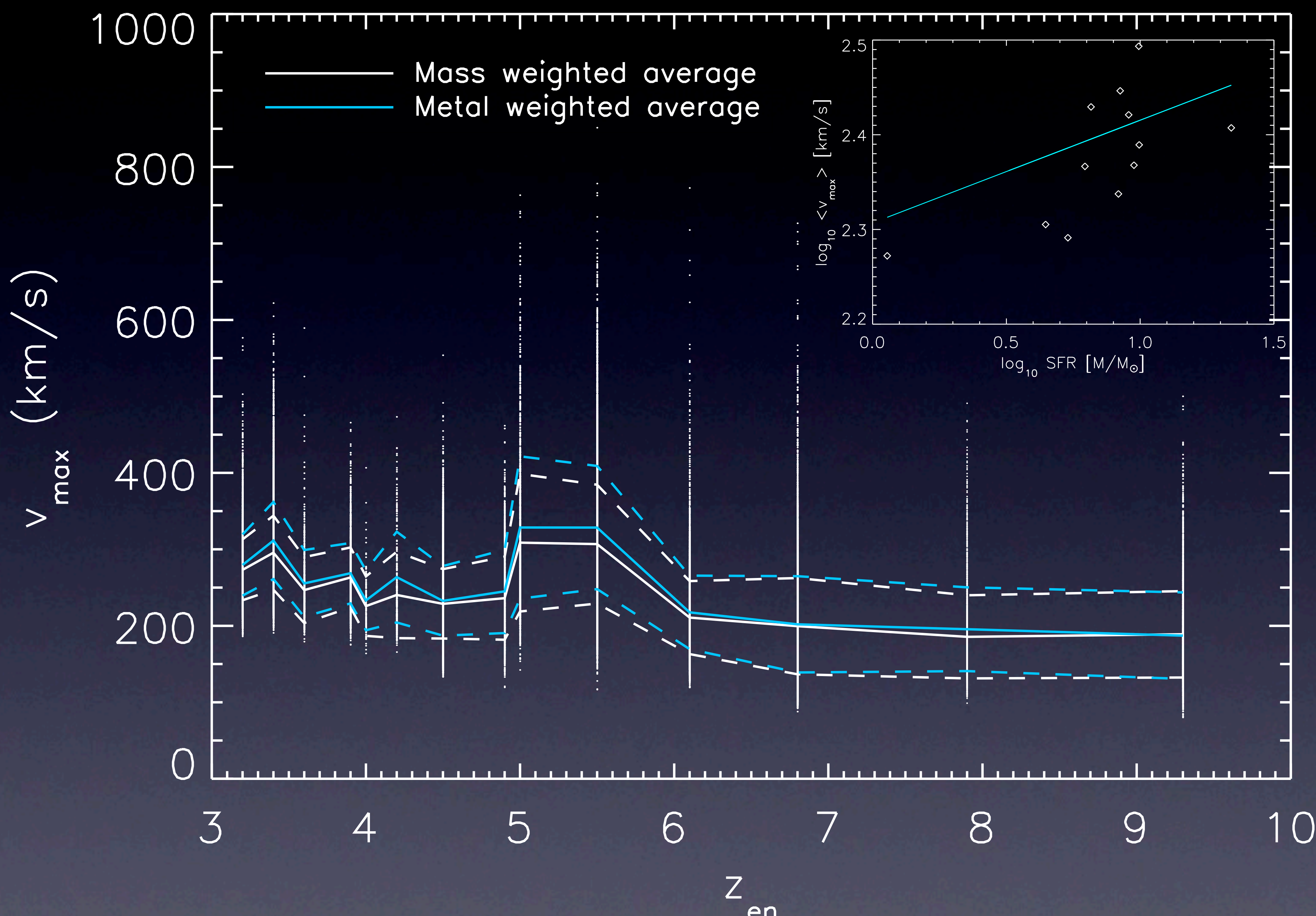
Progenitors vent metals while accreting onto the host

Metals spread around the host while the progenitor is disrupted

Satellite companions also produce metals and dominate the metal pollution at larger distance

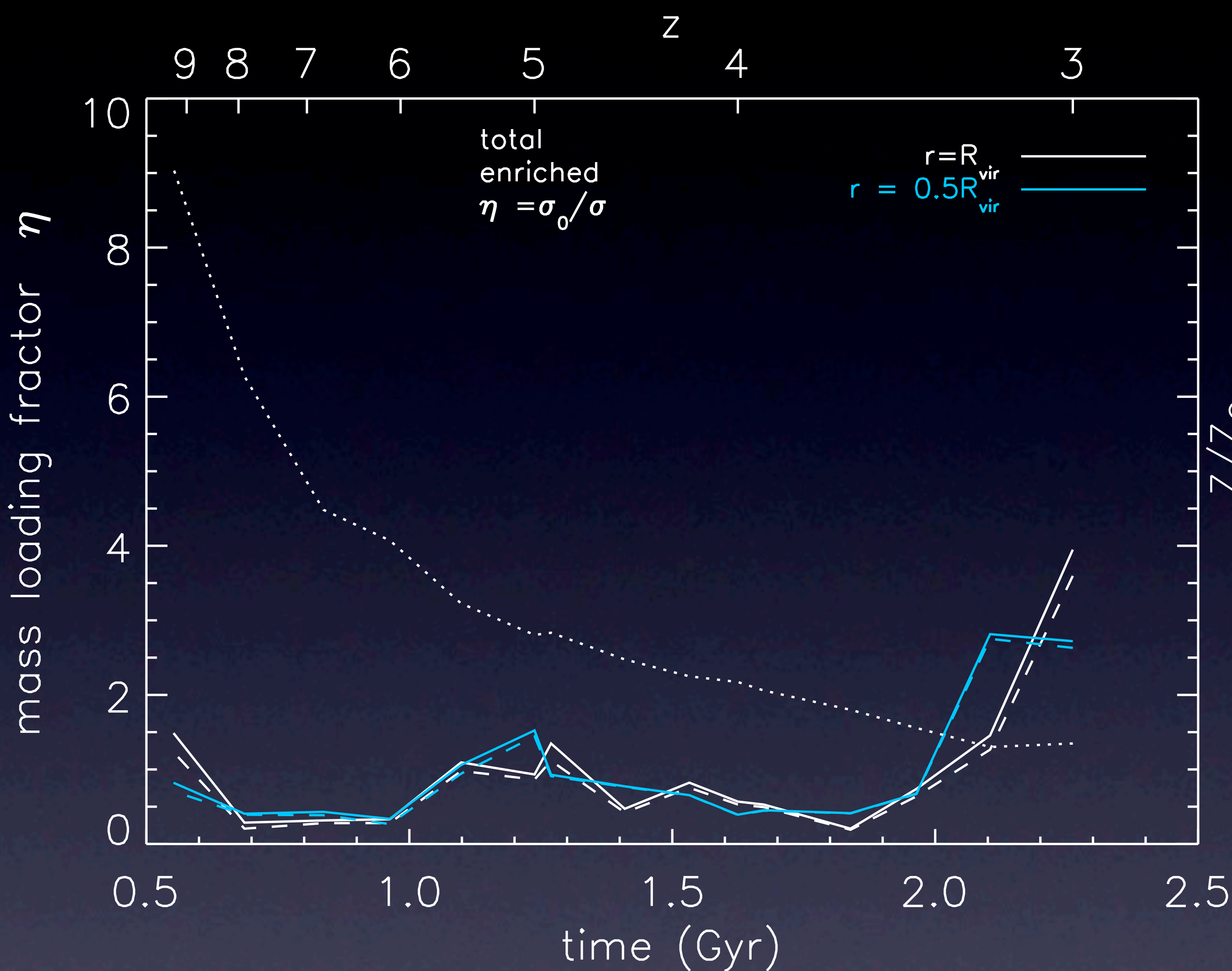
After accretion, enriched material is entrained in the GWs from the host and propagates perpendicular to the disk

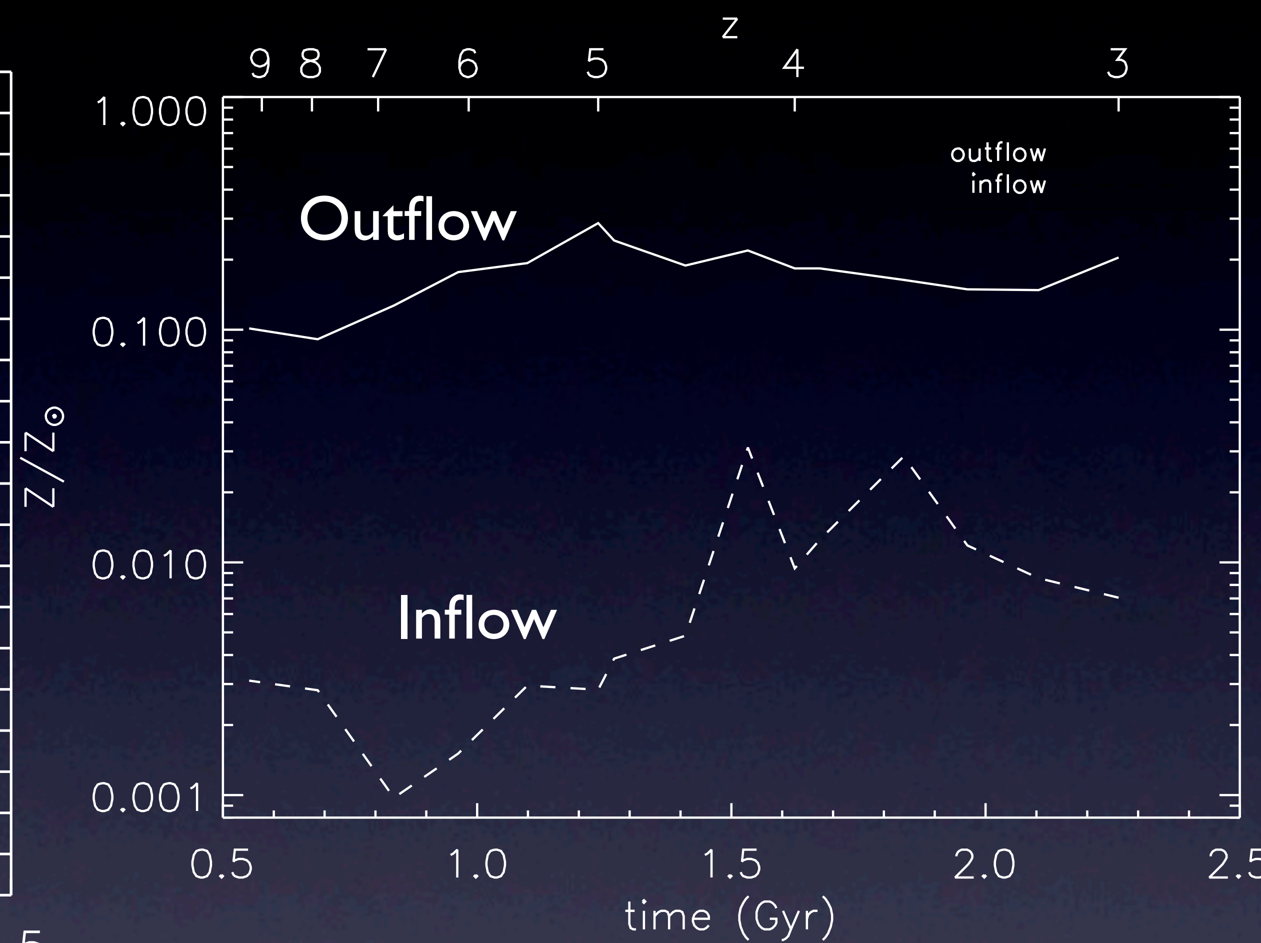
Outflow Properties: Wind Speed



- Outflow radial velocity ~ 100-400 km/s, with maximum up to > 800 km/s;
- v_{eject} has no obvious relation with z (or M_{halo}), but mildly increase with SFR, a relation found in some observations (Veilleux et al. 2005 and references therein)

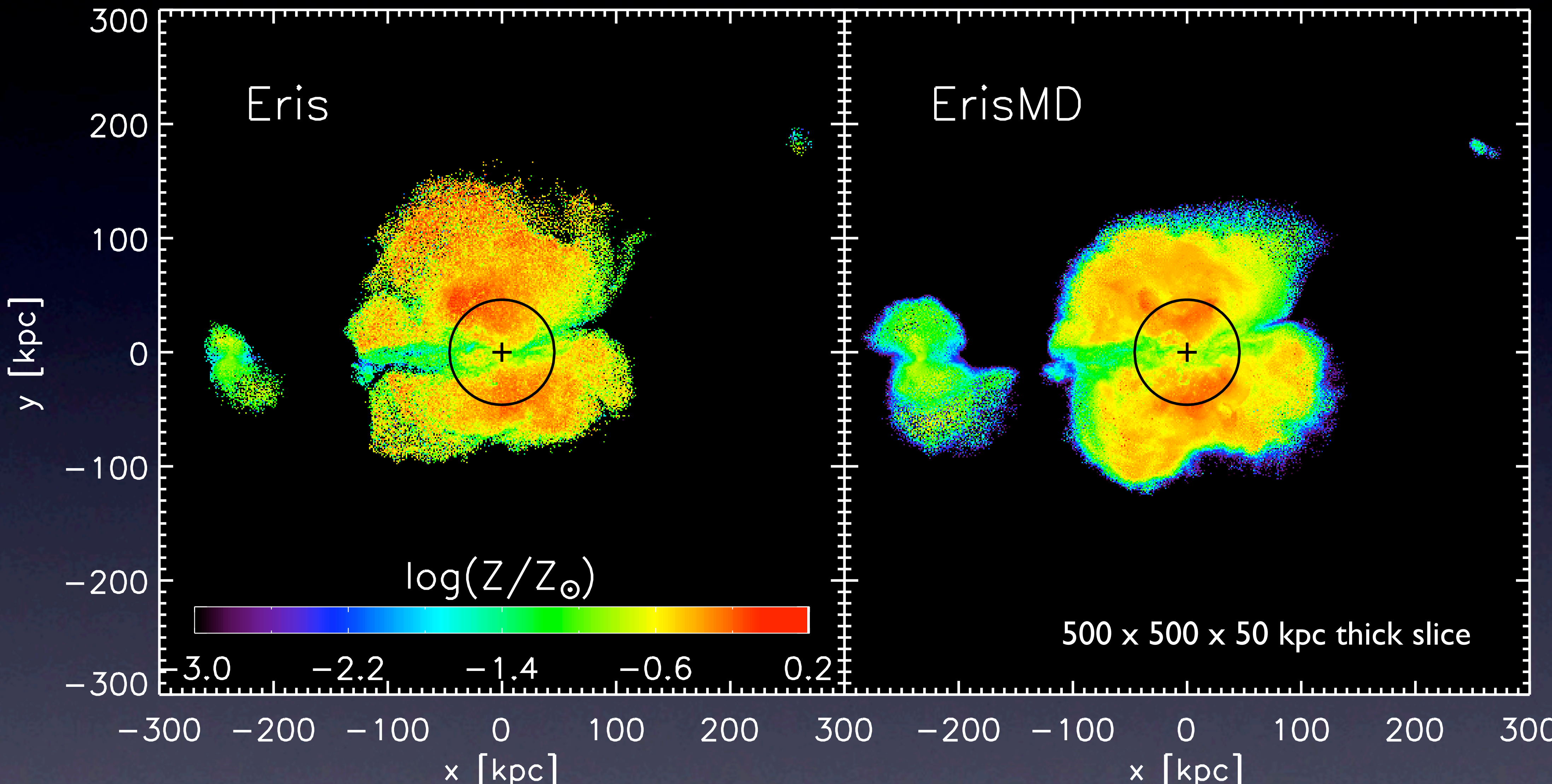
Outflow properties: Mass-loading Factor & Metallicity





- Mass loading $\eta \equiv (dM_w/dt)/SFR$; dM_w/dt calculated at each distance using mass flux
- At 0.5 R_{vir} and R_{vir}, $\eta \sim 0.5 - 4$, roughly constant until z~3.5, with no obvious correlation with M_{halo} or σ
- Outflow $Z/Z_{sun} \sim 0.1$-0.2. roughly constant. Inflow gas increase metallicity from ~ 0.001 Z_{sun} to 0.01 Z_{sun}. -- More satellite contain metals and/or galactic fountain

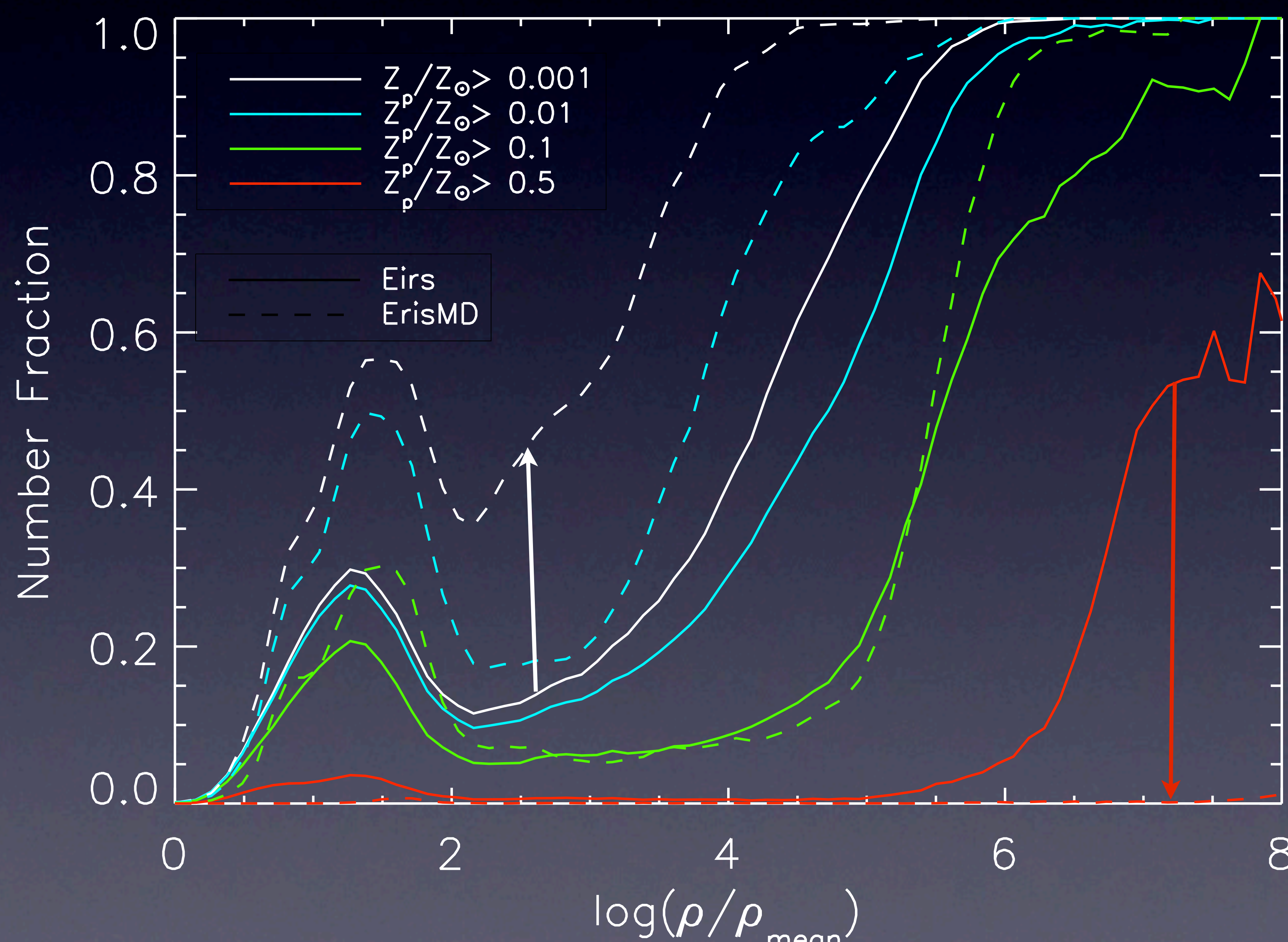
Effect of Turbulent Metal Mixing



- SPH does not mix scalar quantities, metallicity ‘locked’ in gas particles
- ErisMD: same parameters as Eris but with a turbulent diffusion model (Shen et al. 2010). Simulation finish at z ~ 2.5.
- Smagorinsky model (Smagorinsky 1963): mixing proportional to velocity shear

Effect of Turbulent Metal Mixing

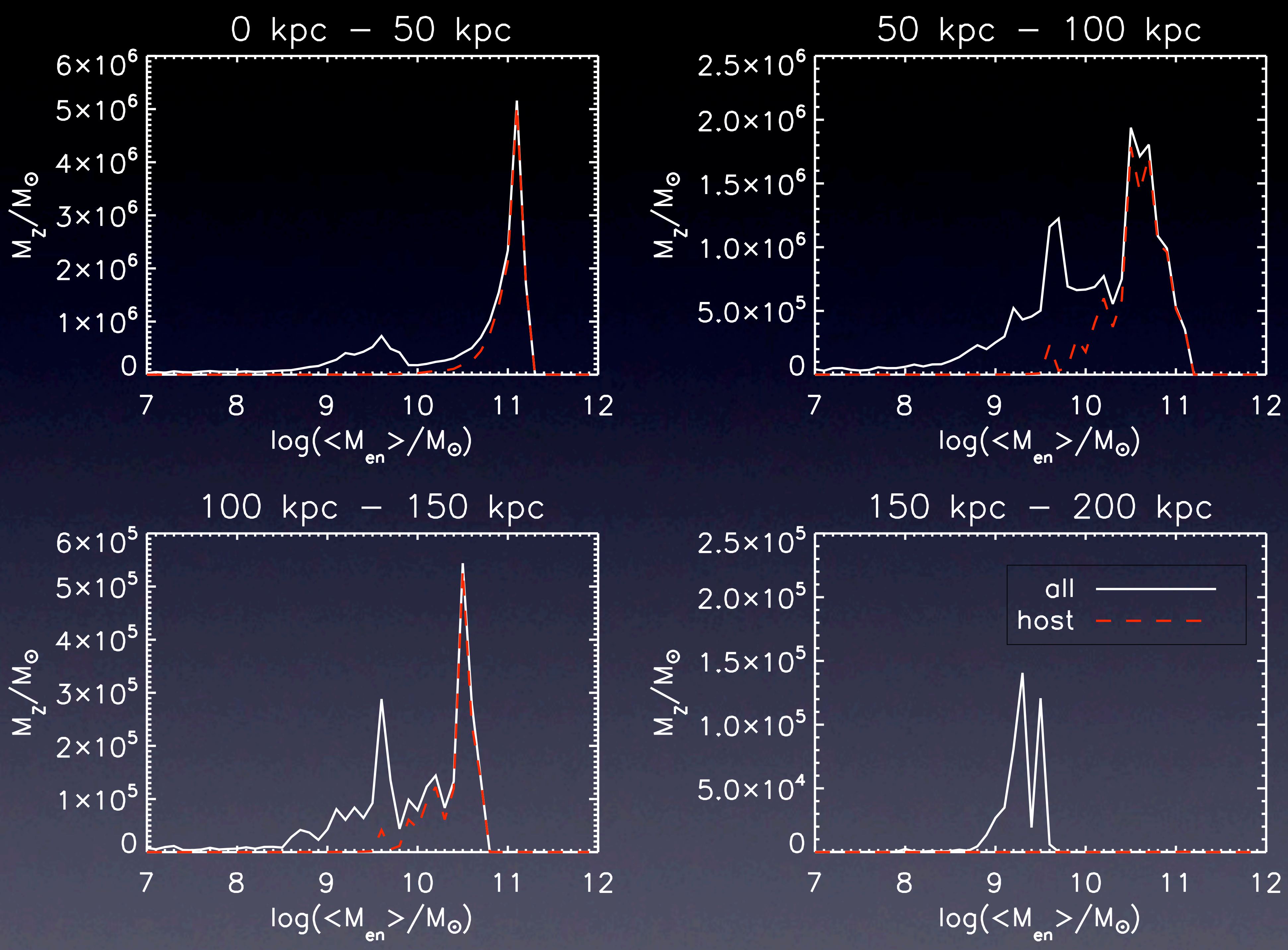
- Increase number of low Z gas particles
- Metal covering factor increases by a factor of 2



Conclusions & Summary

- Metal enrichment in the CGM is a complicated process - the host galaxy, satellite progenitors and satellite companions all contribute to the metals in the CGM
    - Host and its progenitors contributes up to ~ 3 Rvir, satellites companions dominate metal production at r > 3 Rvir
- Metals in low density regions were enriched earlier, ~ 50 % of metals at $\delta \sim 1$ (at z = 3) were ejected at z > 5;
- Satellite progenitors produce metals far away from the host, accrete to the galaxy along filamentary structures. After that, their gas (metals) disrupted and dragged by the large outflows from the host.
- Outflows are enriched to ~ 0.1 Z_{sun} and inflows 0.001-0.01 Z_{sun}, Inflow Z increase with time due to more metal enrich satellites & galactic fountain
- Mixing of metals increases the metal covering factor significantly, hence may affect the detection of metals in the CGM...

Mass of Metal-producing Halos



Smagorinsky Model of Turbulent Diffusion

- Most basic turbulent model: (κ_{Turb} has units of velocity × length)

$$\frac{\partial \bar{u}}{\partial t} + \bar{\mathrm{v}}.\nabla \bar{u} = -(\gamma - 1)\bar{u}(\nabla.\bar{\mathrm{v}}) + \nabla \kappa_{\mathrm{Turb}} \nabla \bar{u}$$

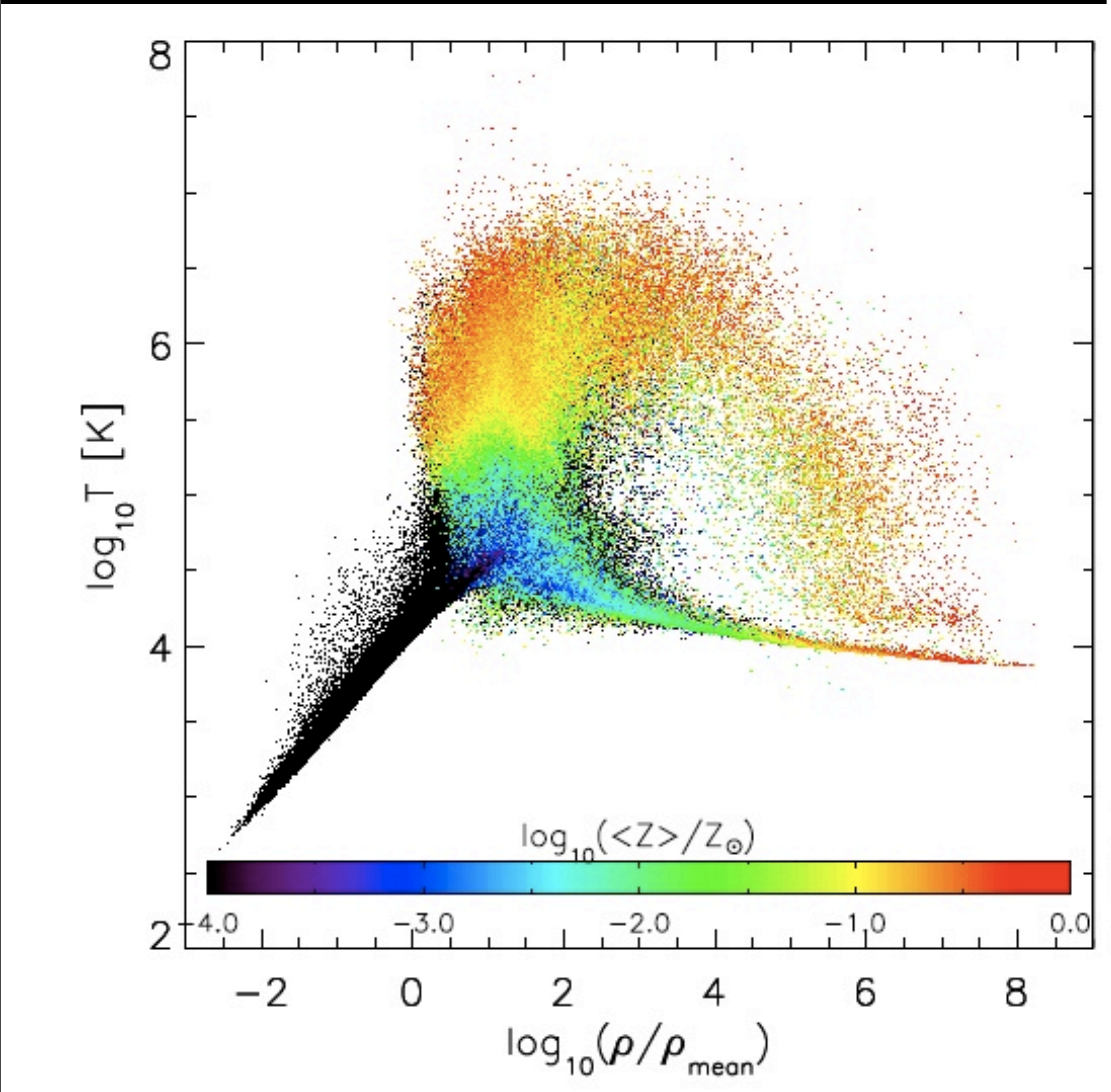
- Smagorinsky model (Mon. Weather Review 1963) -- Diffusion Coefficient determined by velocity Shear

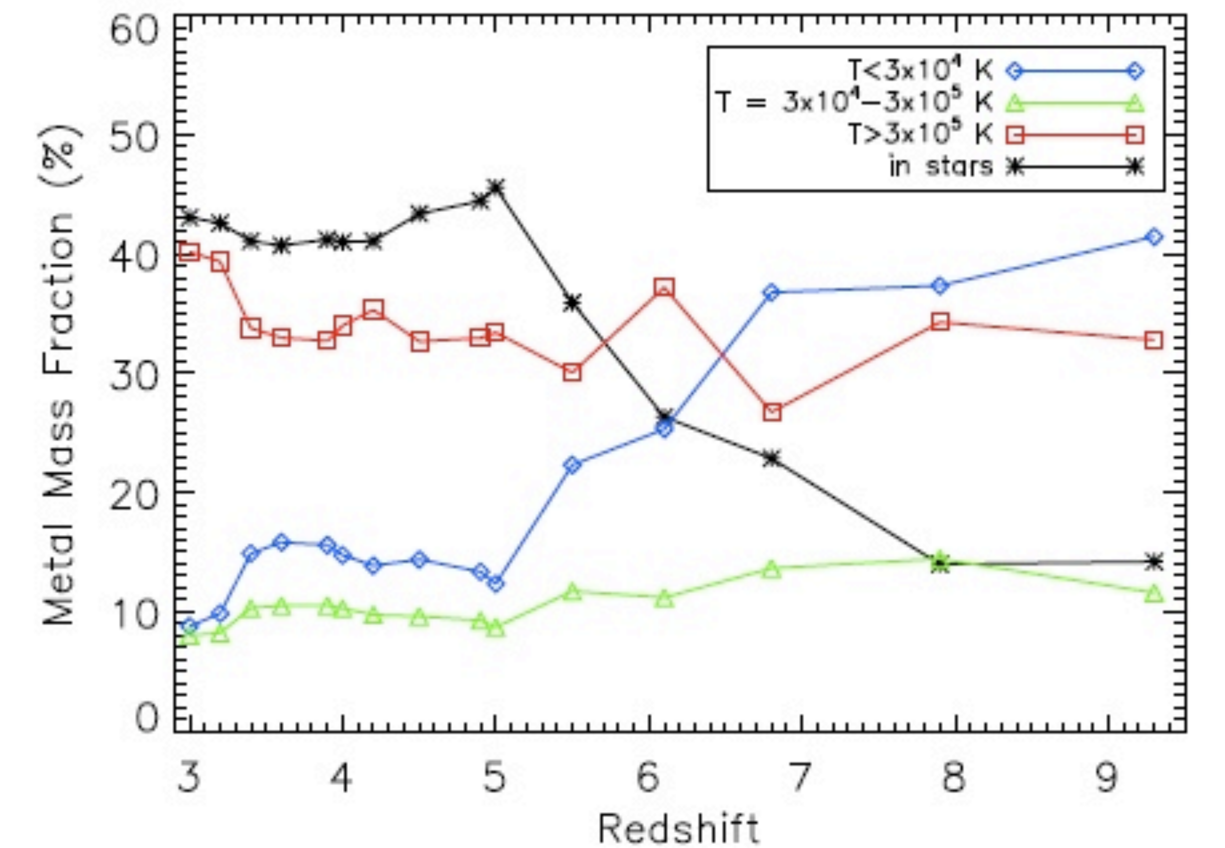
$$\kappa_{Turb} = l_S{}^2 S, \;\; S = \sqrt{S_{ij} S_{ij}}$$

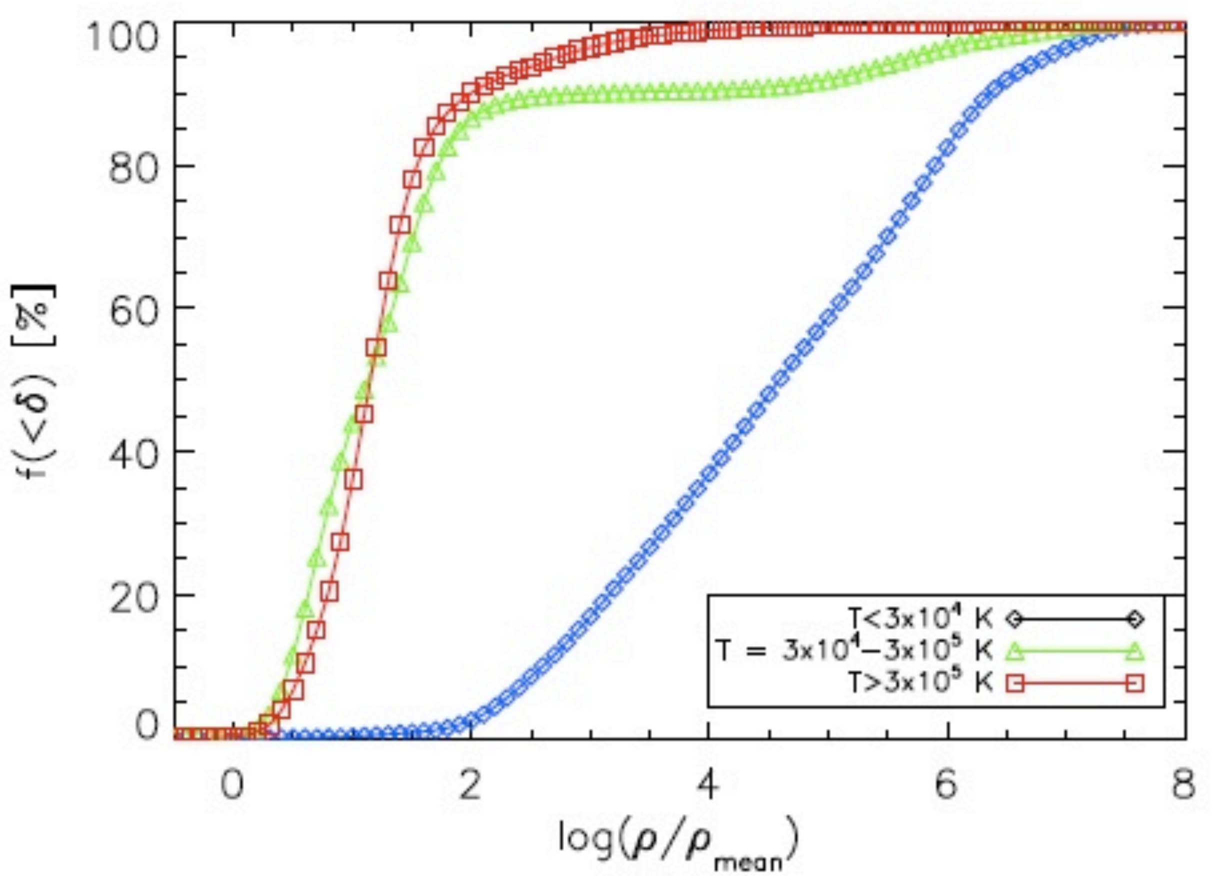
- S_{ij} = trace-free strain rate of resolved flow; l_s = Smagorinsky length. For incompressible grid models $l_s^2 \sim 0.02\ \Delta x^2$

- For SPH we use $\kappa_{Turb} = C\ |S_{ij}| h^2$ with $C \sim 0.05$ (Wadsley, Veeravalli & Couchman 2008; See also Scannapieco & Brüggen 2008, Grief et al 2009)

- After implementation of turbulent diffusion, SPH is able to produce the entropy profile similar to grid codes


log10 T [K]
log10(<Z>/Z⊙)
-4.0
-3.0
-2.0
-1.0
0.0
log10(ρ/ρmean)


T<3x10⁴ K
T = 3x10⁴–3x10⁵ K
T>3x10⁵ K
in stars
Metal Mass Fraction (%)
Redshift


T<3x10⁴ K
T = 3x10⁴–3x10⁵ K
T>3x10⁵ K
f(<δ) [%]
log(ρ/ρmean)