Galactic outflows and the IGM

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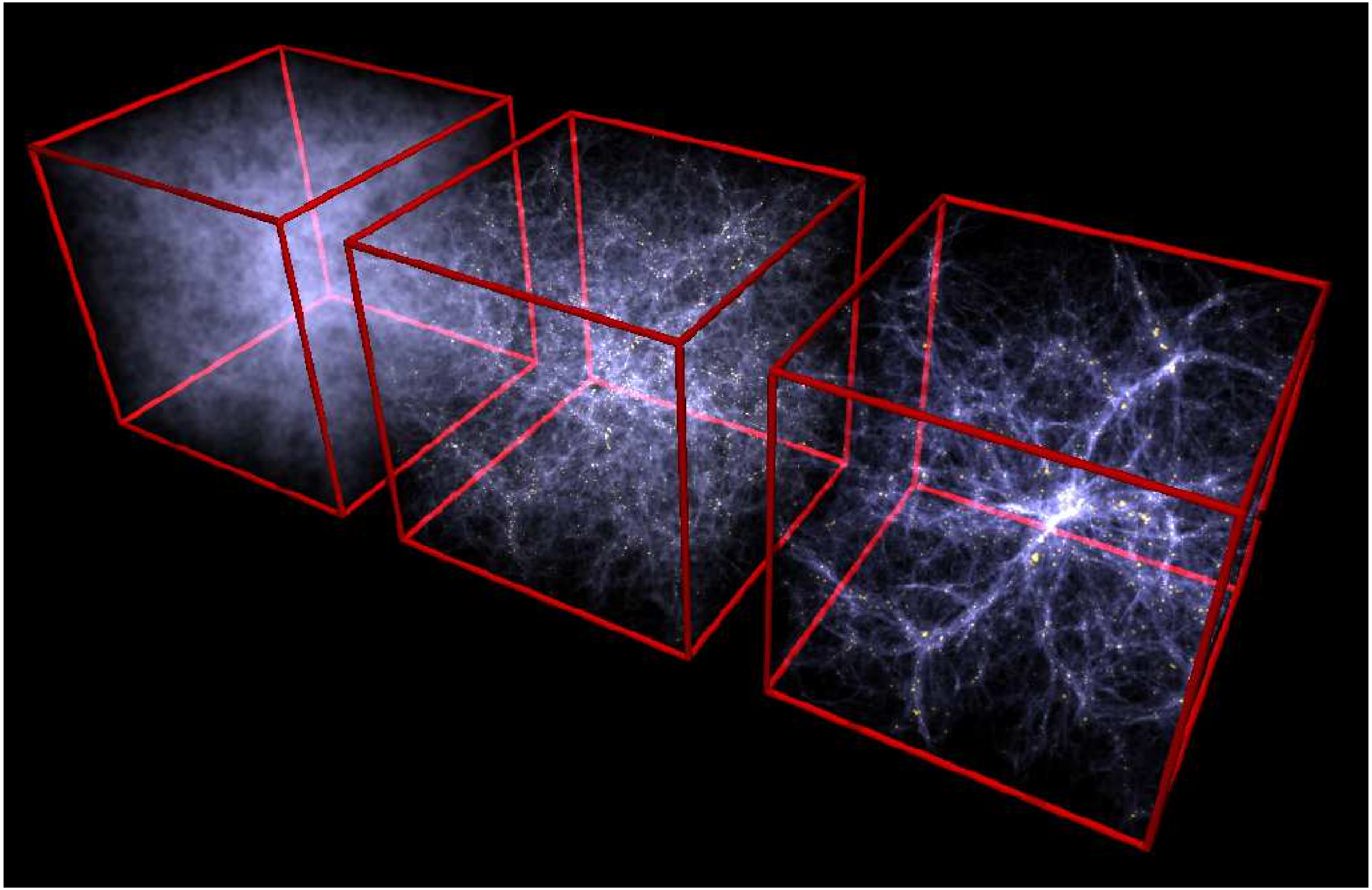
Plan

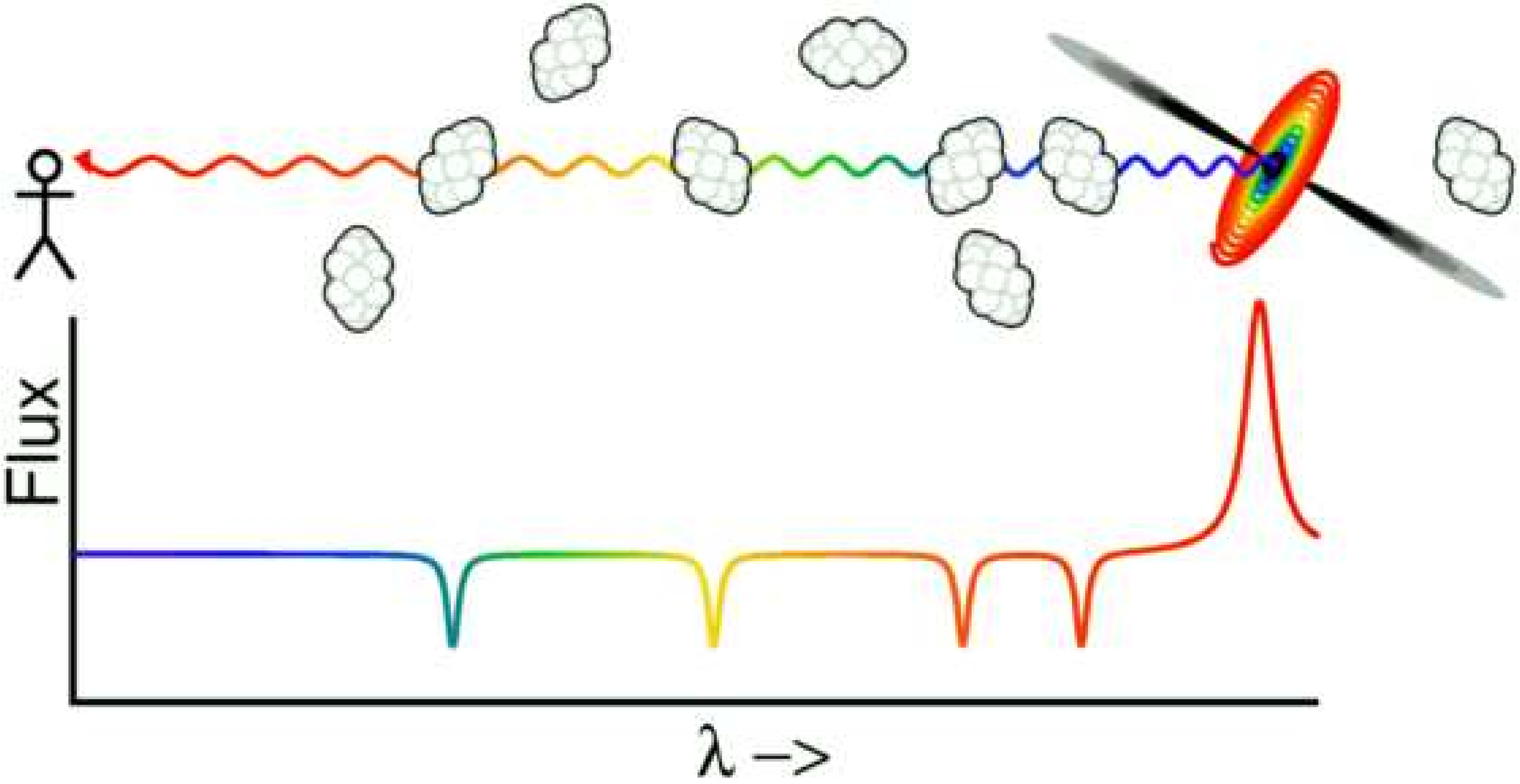
- The Lyman-α forest and IGM metals
- Paradigm for an outflow
- Properties of individual outflows
- Global impact of outflows
- Conclusions

Structure formation in universe



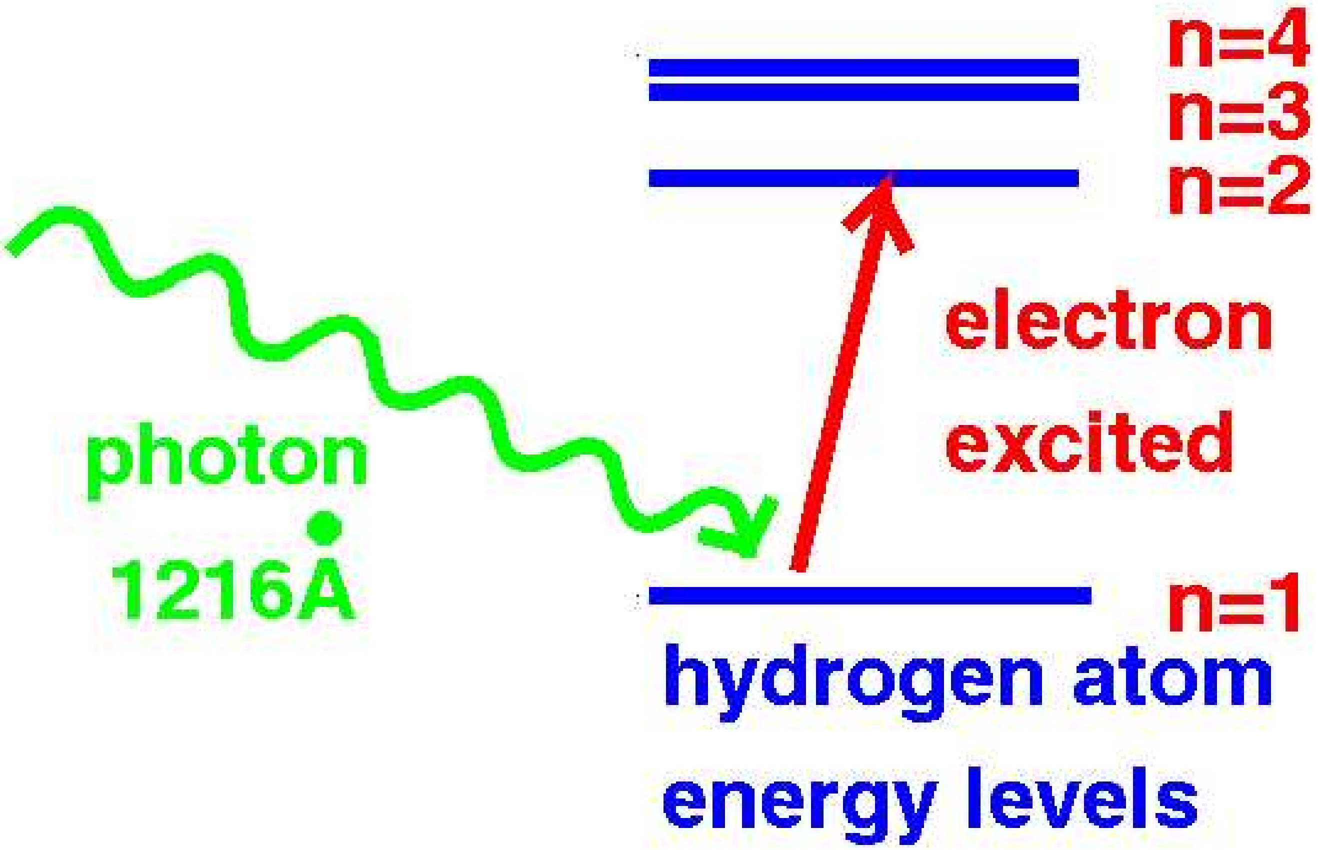
Springel and Herquist, 2003

Quasar absorption lines



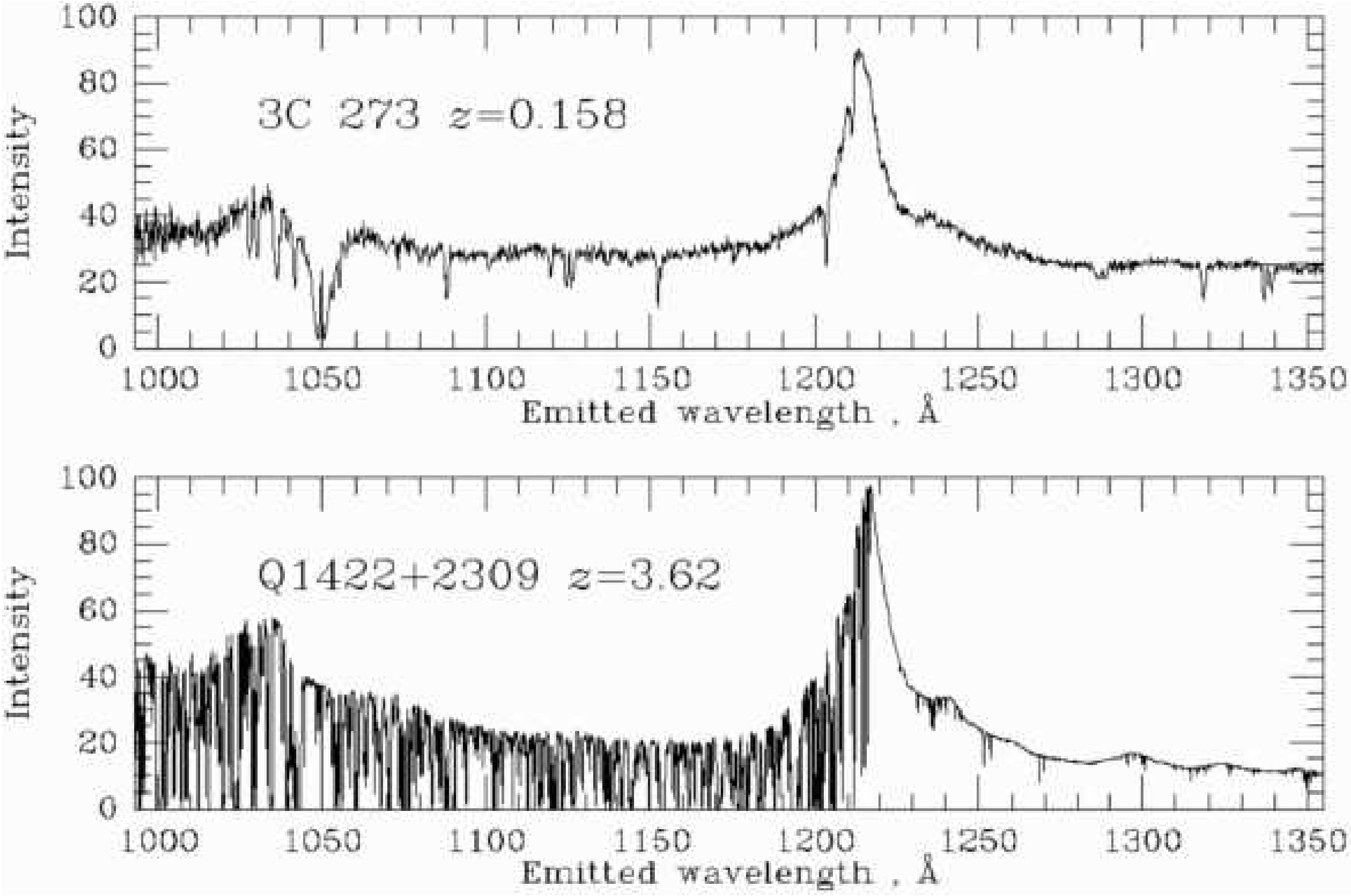
www.astro.ucla.edu/ wright

The Lyman-α line



http://astro.berkeley.edu/ jcohn/lya.html

The Lyman-α forest



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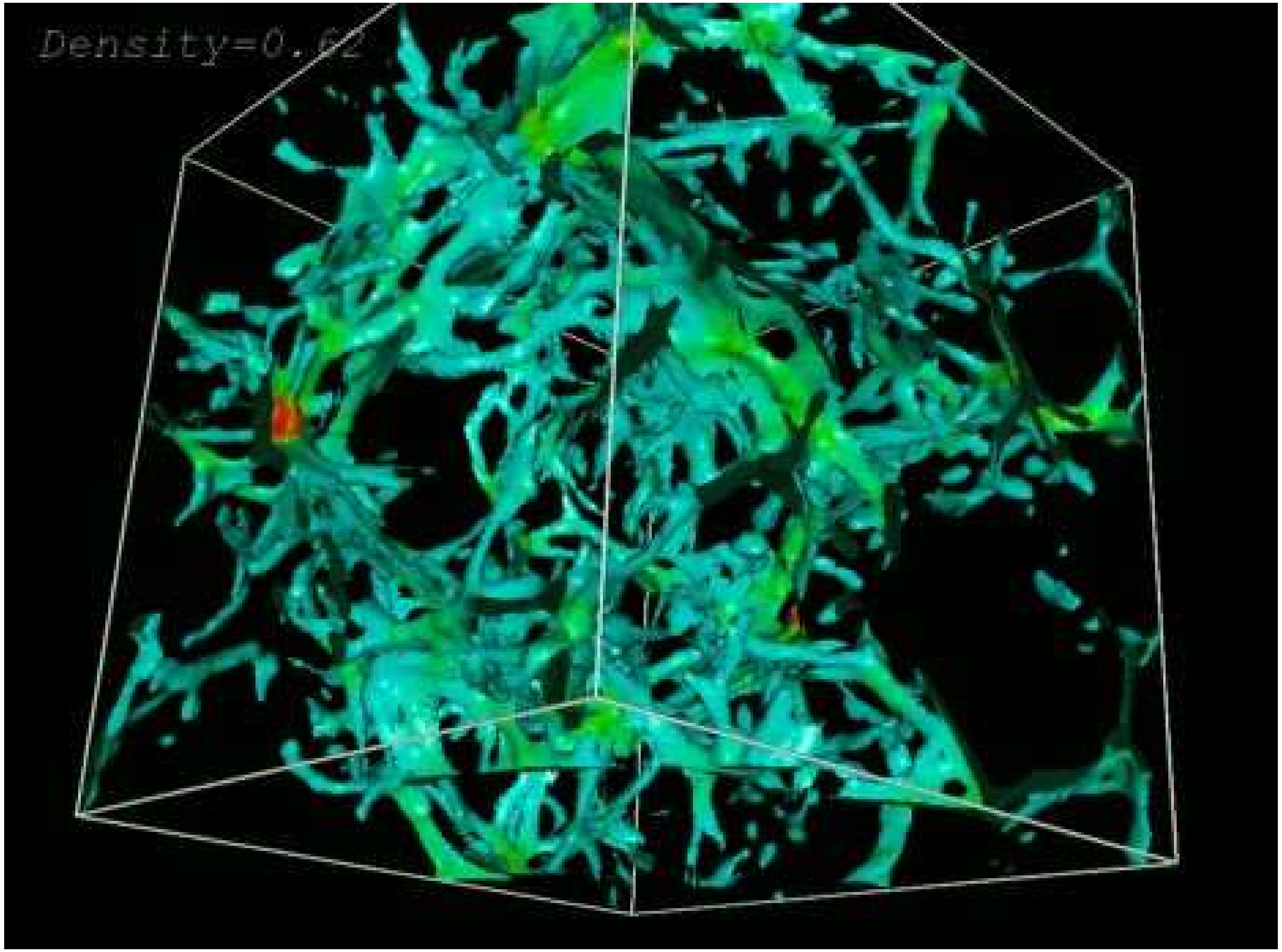
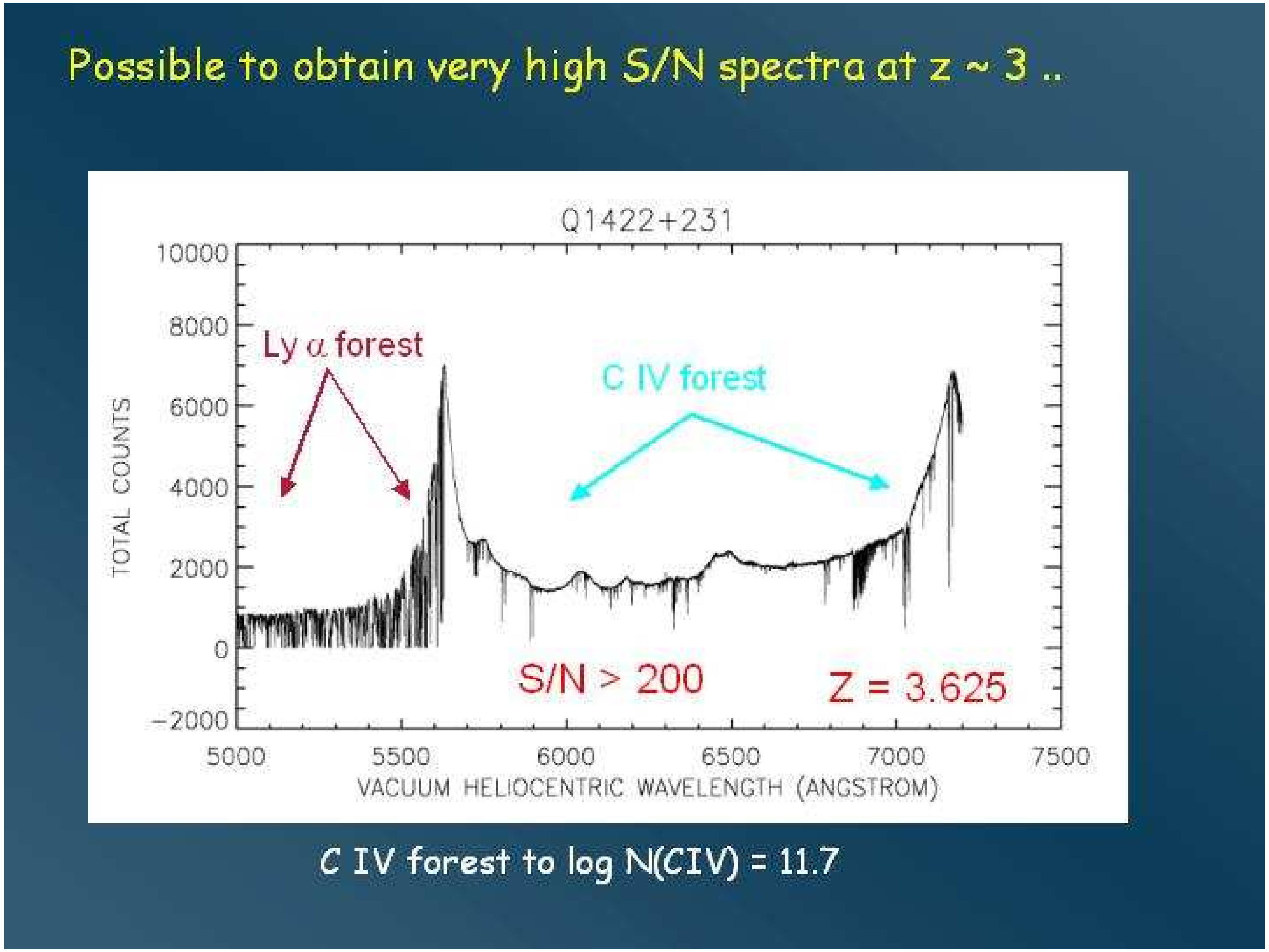
Ly-α forest from IGM



J. Shalf, Y. Zhang et al, 1998

Metals associated with Ly-α forest



Possible to obtain very high S/N spectra at z ~ 3 ..

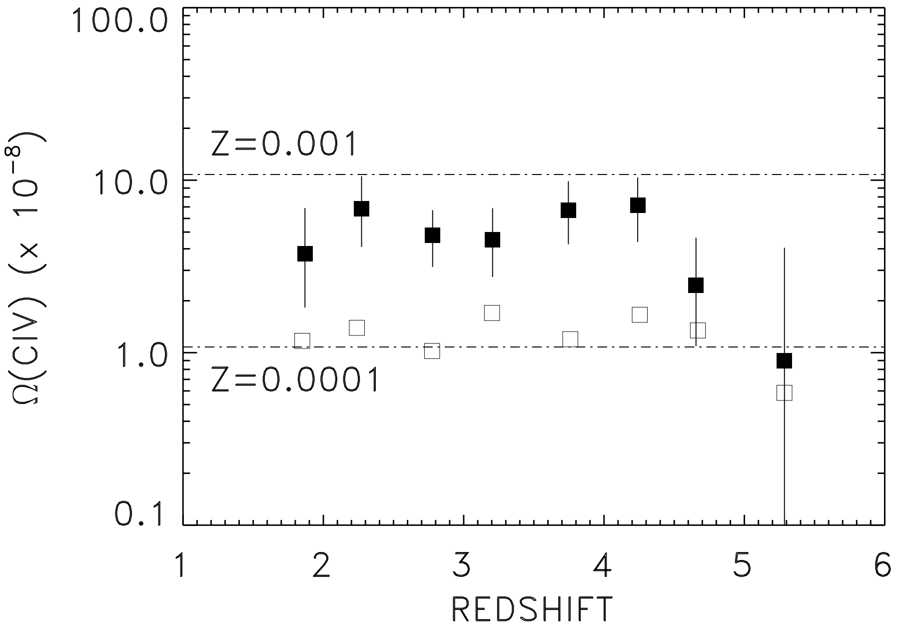
C IV forest to log N(CIV) = 11.7

A. Songaila, 2004, KITP talk (CIV 1548,1550 doublet)

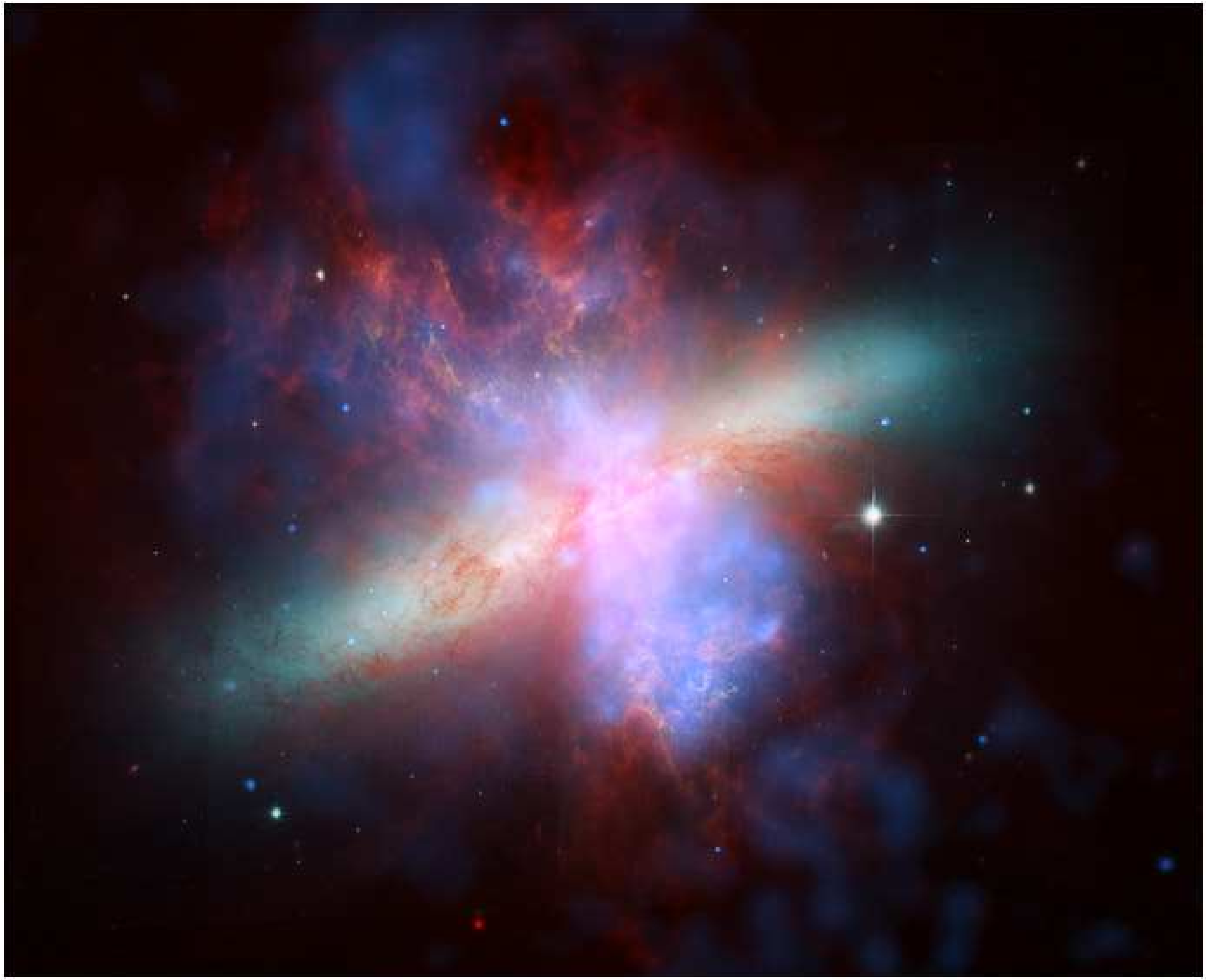
Metals associated with Ly-α forest

- Detection of metal lines associated with Ly-α: CIV, SiIV, OVI
- Pixel statistics $\Rightarrow$ metals even in low density IGM?
- How did they get there? Galactic outflows?

Songaila, ApJ, 561, L153, 2001



Outflow from Starburst galaxy M82



NASA website

Modeling the Star formation

Star formation Key to outflows. Use constrained model of:

Samui, Srianand & Subramanian , 2007, MNRAS, 377, 285

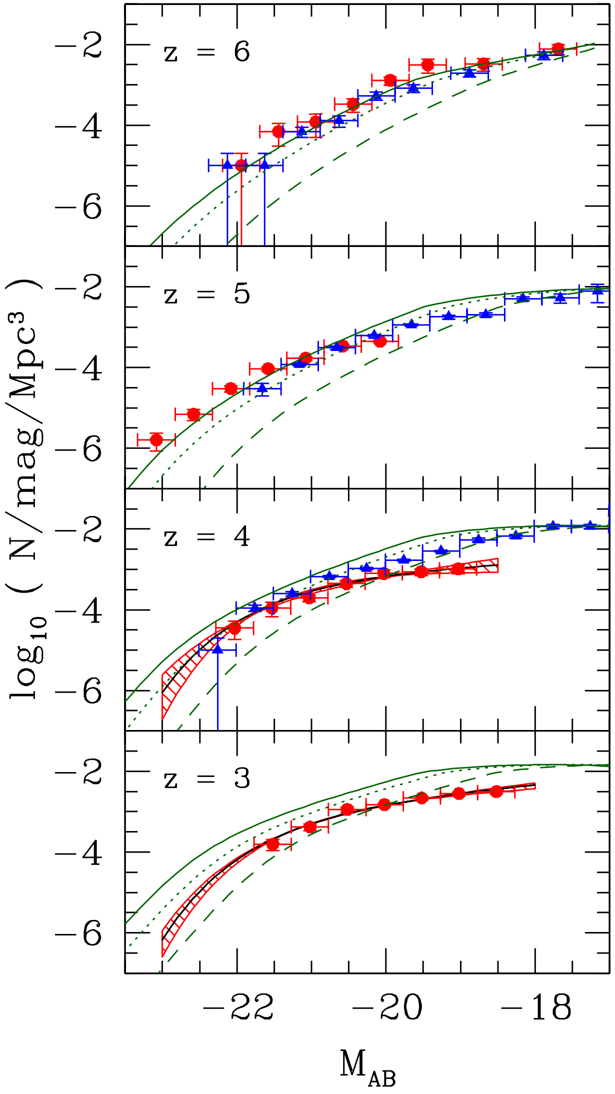
- Star fomation rate in a halo

$$\dot{M}_{\rm SF}(M,z,z_c) = f_* \left(\frac{\Omega_b}{\Omega_m} M\right) \frac{t(z)-t(z_c)}{\kappa^2 t_{\rm dyn}^2(z_c)} \exp\left[-\frac{t(z)-t(z_c)}{\kappa t_{\rm dyn}(z_c)}\right]$$

- UV luminosity got for given SFR and IMF
- Modified Press-Schechter formalism to get halo number density
- Self-consistent reionization feedback
- Both atomic cooled and molecular cooled halos
- To fit the luminosity functions/SFR density
  - $f_* = 0.50$, $\kappa = 1.0$, WMAP 3yr cosmology, Salpeter IMF
  - Molecular cooled halos not directly detectable but affect ionization history and hence the LF

Modeling high-z UV Luminosity functions

Salpeter IMF with lower cut-off's $1M_\odot, 0.5M_\odot, 0.1M_\odot$

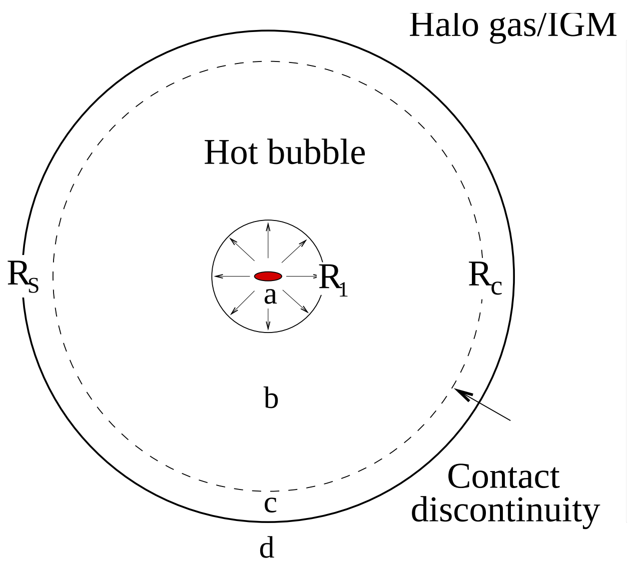


The general outflow scenario

- SNe creates hot bubble of shock heated gas
- Clustered SNe leads to formation of super bubble
- Galaxy blows a wind of hot gas (cool ’clouds’) into the halo
- Model this like a stellar wind blown bubble.
- Luminosity input continuous: $L(t) = 10^{51} \times \epsilon_{\rm w}\ \nu\ \dot{M}_{\rm SF}$ erg s^{-1}
- ν: No. of SNe per $M_\odot$ stars; $\epsilon_{\rm w}$: Kinetic efficiency
- Mass input: $\dot{M}_w = \eta \dot{M}_{SF}$
- Assume thin shell approximation and spherical symmetry
- Calculate individual outflows, then global effects on IGM

Structure of Outflow : Pressure driven

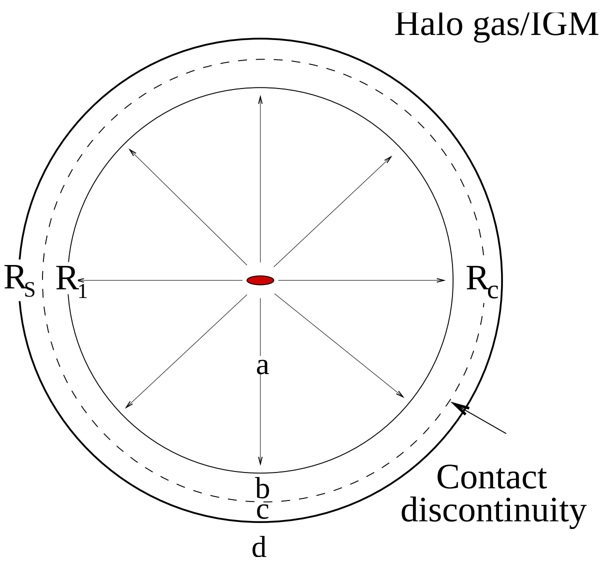
- Onion-like structure with 4 concentric zones:



- (a) the galactic wind blowing out ($r < R_1$)
- Inner shock at R_1
- (b) hot bubble of shocked wind gas ($R_1 < r < R_c$)
- (c) thin dense shell of shocked IGM/halo
- Contact discontinuity at (R_c) and outer shock at R_s
- (d) undisturbed halo/IGM gas outside ($r > R_s$)

Structure of Outflow : Momentum driven

- If hot bubble cools efficiently by radiating energy:
- R_1 catches up with R_s
- Free winds give momentum to the shell



Modeling the outflow dynamics

- Assume thin shell approximation and spherical symmetry
- The evolution of the outflows is governed by

$$m_s(R_s)\frac{\mathrm{d}^2R_s}{\mathrm{d}t^2} = 4\pi R_s^2\,(P_b - P_0) - \dot{m}_s(R_s)(\dot{R}_s - v_0(R_s)) - \frac{GM(R_s)m_s(R_s)}{R_s^2}$$

$$\frac{\mathrm{d}m_s}{\mathrm{d}t}(R_s) = \epsilon 4\pi R_s^2\rho_B(R_s)(\dot{R}_s - v_0(R_s))$$

$$P_b = \frac{E_b}{2\pi(R_s^3 - R_1^3)}$$

$$\frac{\mathrm{d}E_b}{\mathrm{d}t} = L(t) - \Lambda(t,Z) - 4\pi(R_s^2\dot{R}_s - R_1^2\dot{R}_1)P_b$$

$$P_b = \frac{3}{4}\frac{\dot{M}_w(t_e)}{4\pi R_1^2 v_w}\left[v_w - \dot{R}_1\right]^2$$

Metallicity and Cooling of the bubble

- Metallicity of the bubble
  - $\dot{M}_w = \eta \dot{M}_{SF}$
  - $0.1\ M_\odot$ of carbon per SNe for normal Salpeter IMF
  - Instantaneous mixing of metals
  - Compute mass of the ejected metals

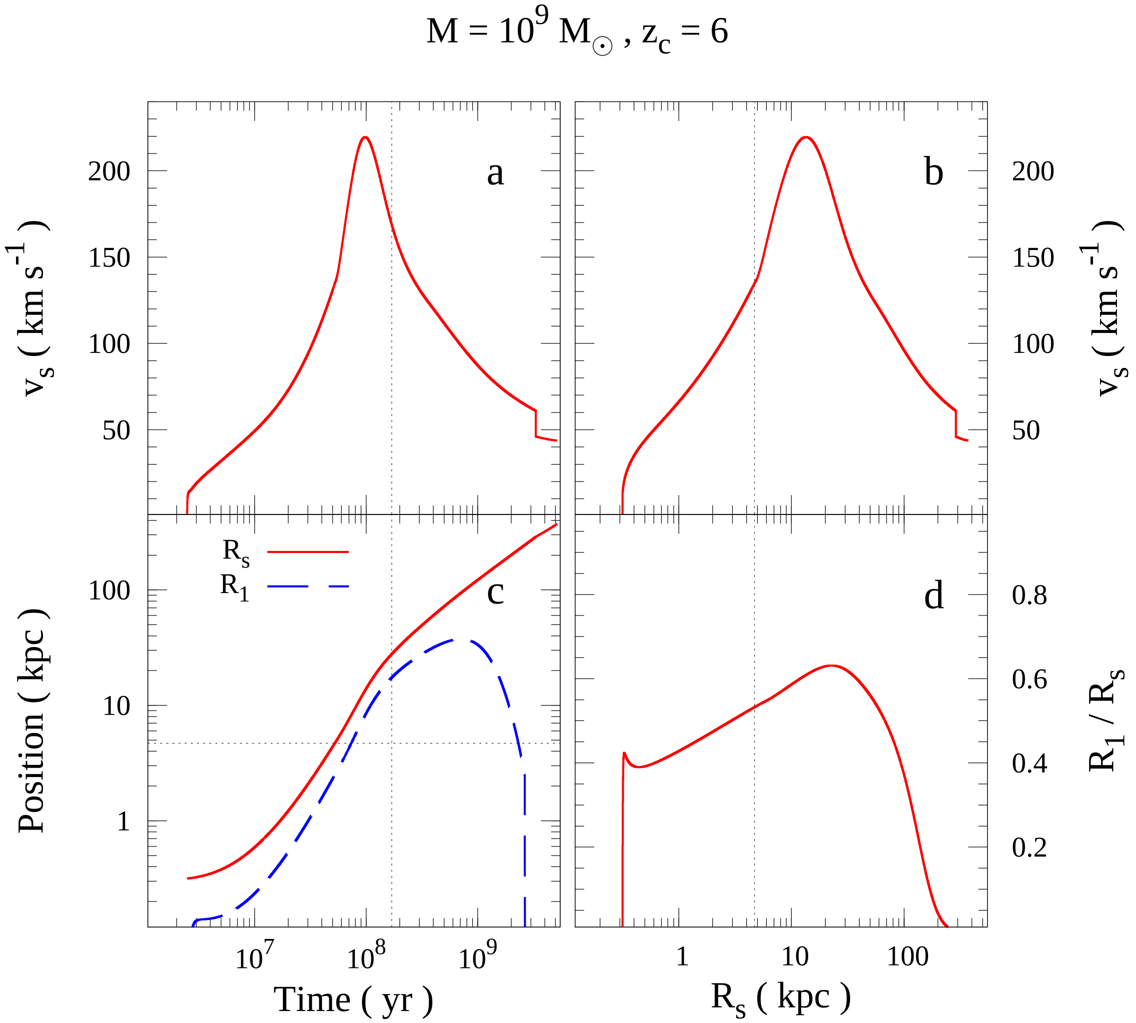
$$m_h = \frac{\eta p}{(1+\eta)^2} M_0 \left[(1+\eta)\frac{M_s}{M_0} + \left(1-(1+\eta)\frac{M_s}{M_0}\right) \ln\left(1-(1+\eta)\frac{M_s}{M_0}\right) \right]$$

- Cooling of the bubble
  - Recombination line cooling (depends on metallicity)
  - Compton drag against the CMBR
  - Bremsstrahlung

Initial conditions

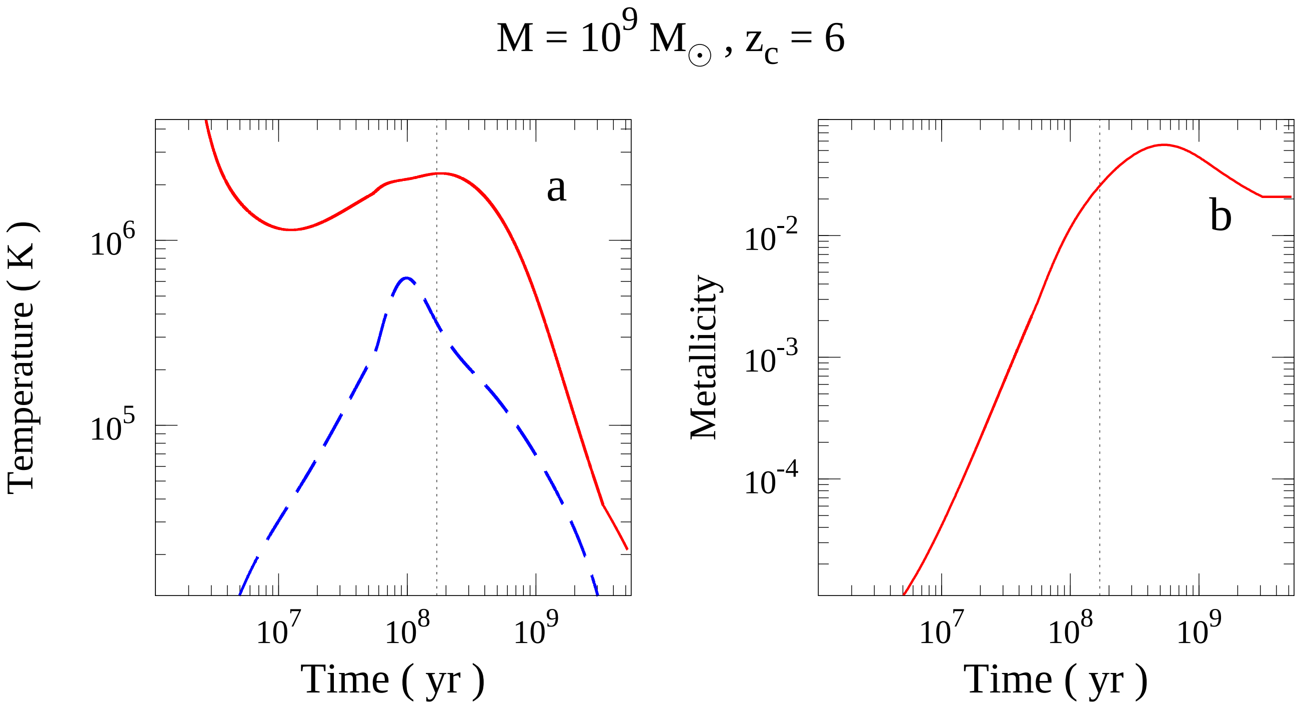
- $R_s = R_{\rm vir}/15$
- $v_s = 0$
- $R_1 = 0$
- t_{ins} when $P_b > P_0$
- Stopping condition : $v_s < c_s$
- Transition to momentum driven phase : $R_1/R_s = f_c$

Structure of an outflow from $10^9 M_\odot$ halo

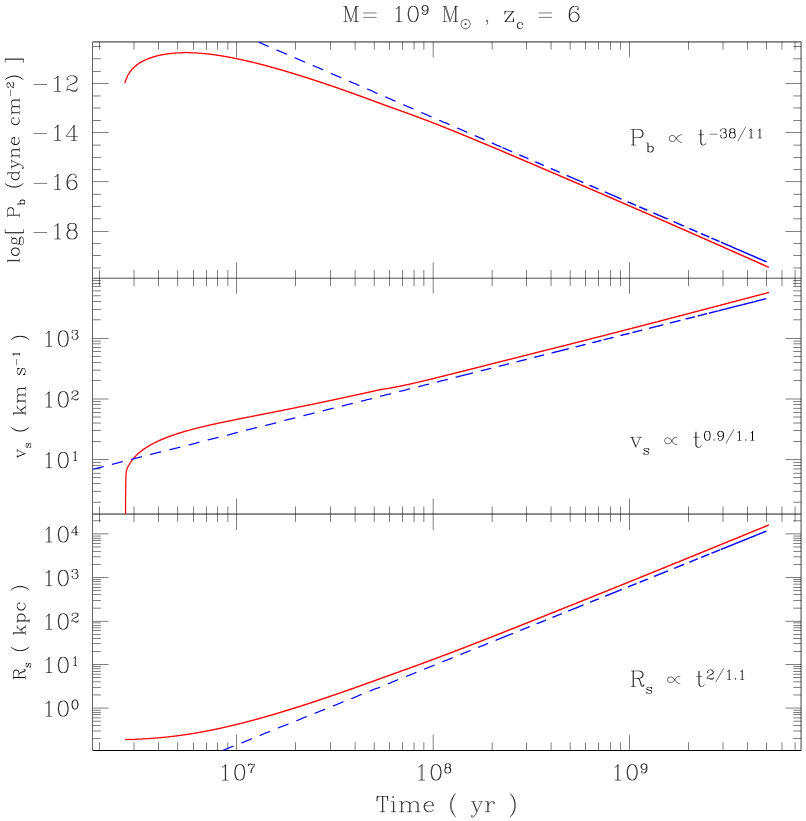


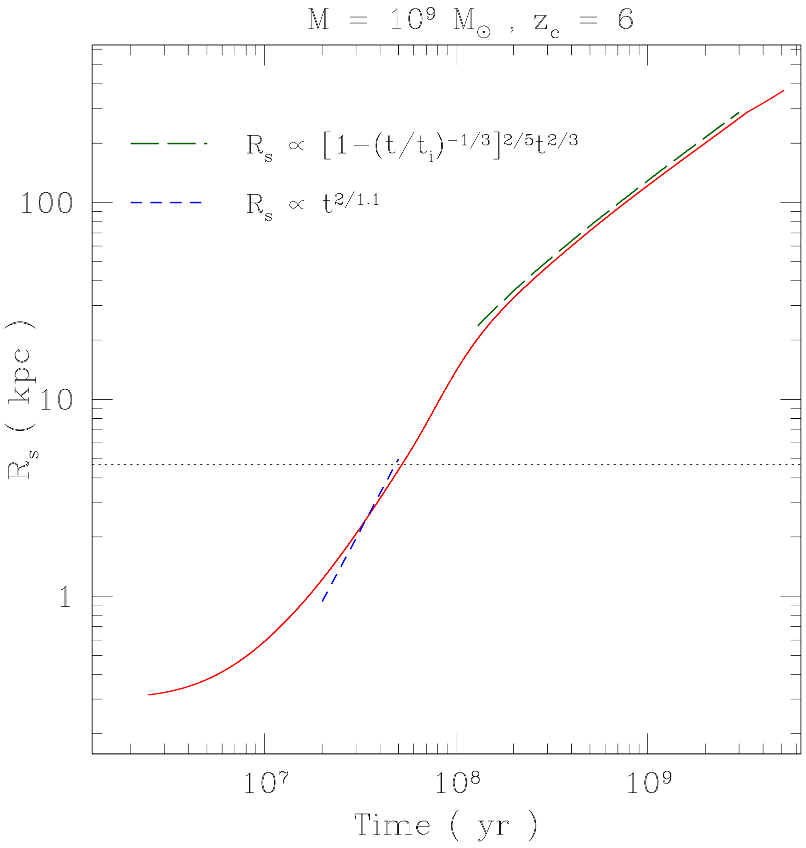
$$f_h = 0.1,\ \epsilon = 0.9,\ \epsilon_w = 0.1,\ \eta = 0.3,\ \nu^{-1} = 50\ M_\odot$$

Temperature and metallicity



Comparison with scale-free solution





Outflow properties

- Outflows generically escape from $M < 10^9 M_\odot$ halos. Final velocity, radius insensitive to
  - initial R_s, v_s, t
  - Halo mass fraction or mass loading from galaxy
- Final radius proportional to energy input efficiency (ϵ_w, ν, f_*)
- Continuous star formation mode more effective than bursts
- Shell gas cools efficiently while in halo but not in the IGM
- `Pressure driven' outflows more generic especially for low η
- Acceleration phase can lead to shell fragmentation due to R-T instability: but does not affect final results

Global properties of Outflows

- Porosity is defined as :

$$Q(z) = \int_{M_{\rm low}}^{\infty} {\rm d}M \int_{z}^{\infty} {\rm d}z' \, \frac{{\rm d}^2 N(M,z,z')}{{\rm d}z' \, {\rm d}M} \, \frac{4}{3}\pi \left[R_S(1+z)\right]^3$$

- Filling factor

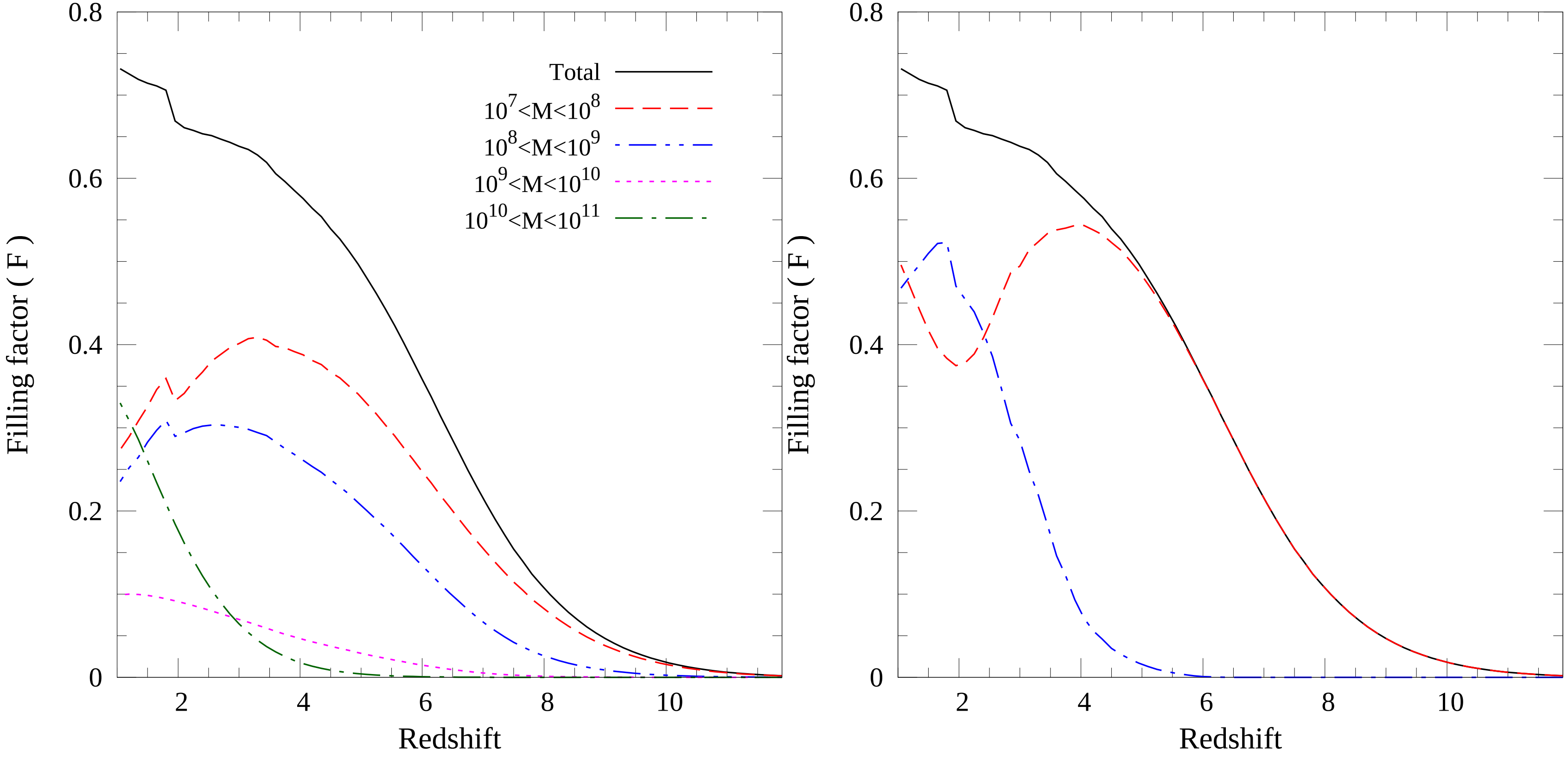
$$F = 1 - \exp(-Q)$$

- Porosity weighted average for any physical quantity X

$$\langle X \rangle = Q^{-1} \int_{M_{\rm low}}^{\infty} {\rm d}M \int_{z}^{\infty} {\rm d}z' \, \frac{{\rm d}^2 N(M,z,z')}{{\rm d}z' \, {\rm d}M} \, \frac{4}{3}\pi \left[R_S(1+z)\right)^3 X$$

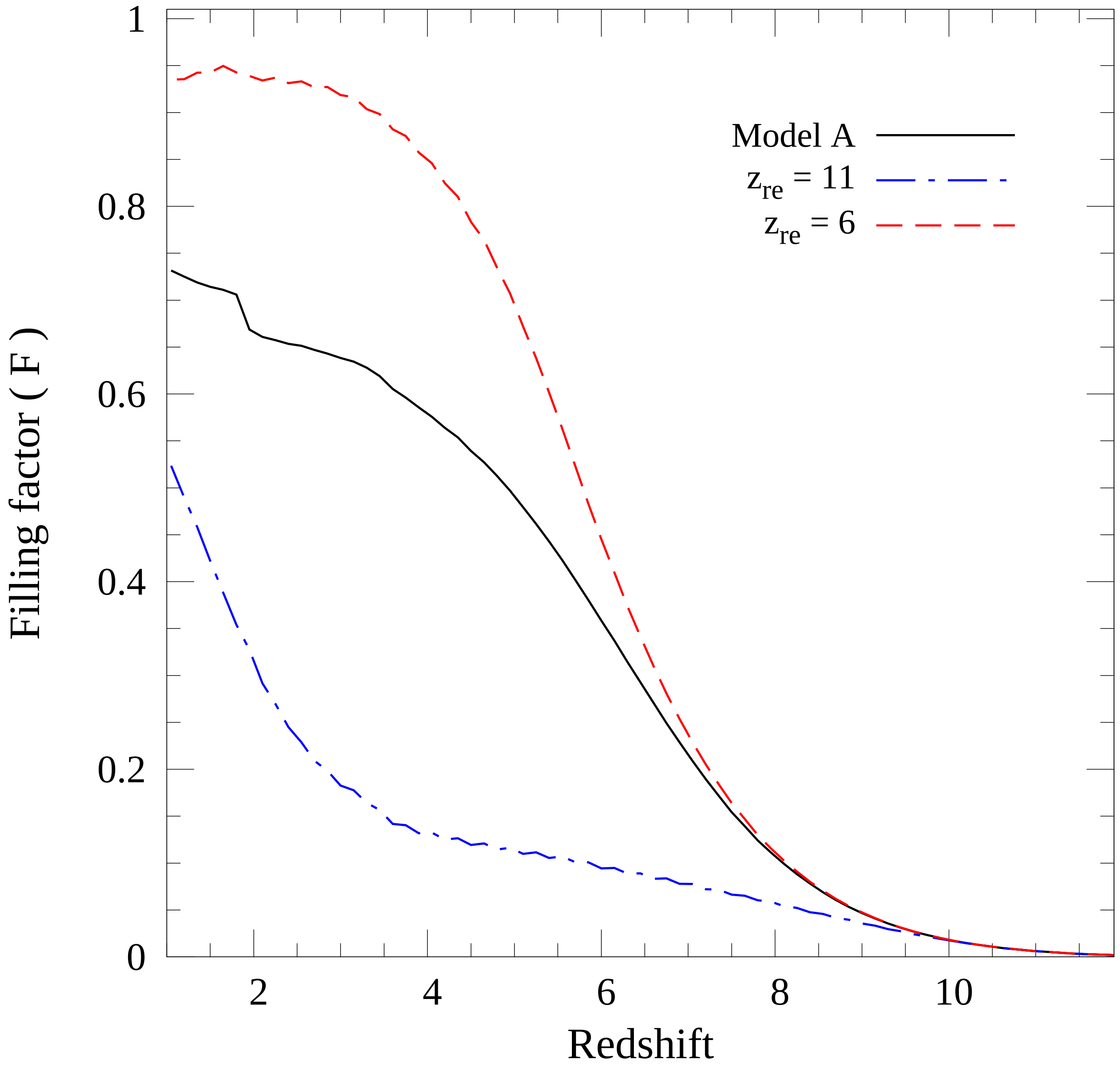
- Can also compute differential and cumulative PDFs

Filling factor : Atomic cooling model

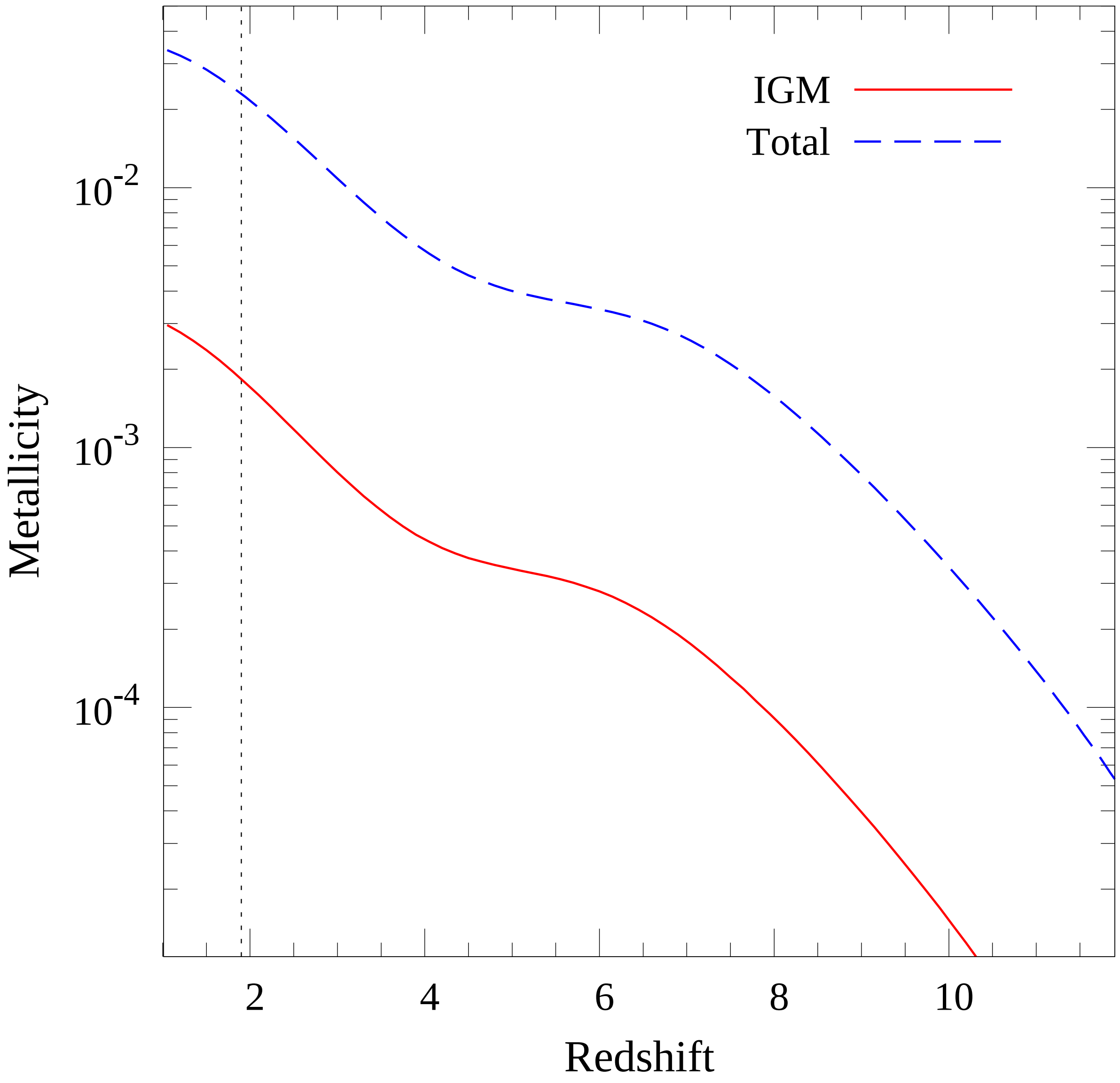


- Outflows from $10^7 - 10^9 M_\odot$ halos dominated volume filling.
- Comparable number of active and Hubble frozen flows at $z = 3$

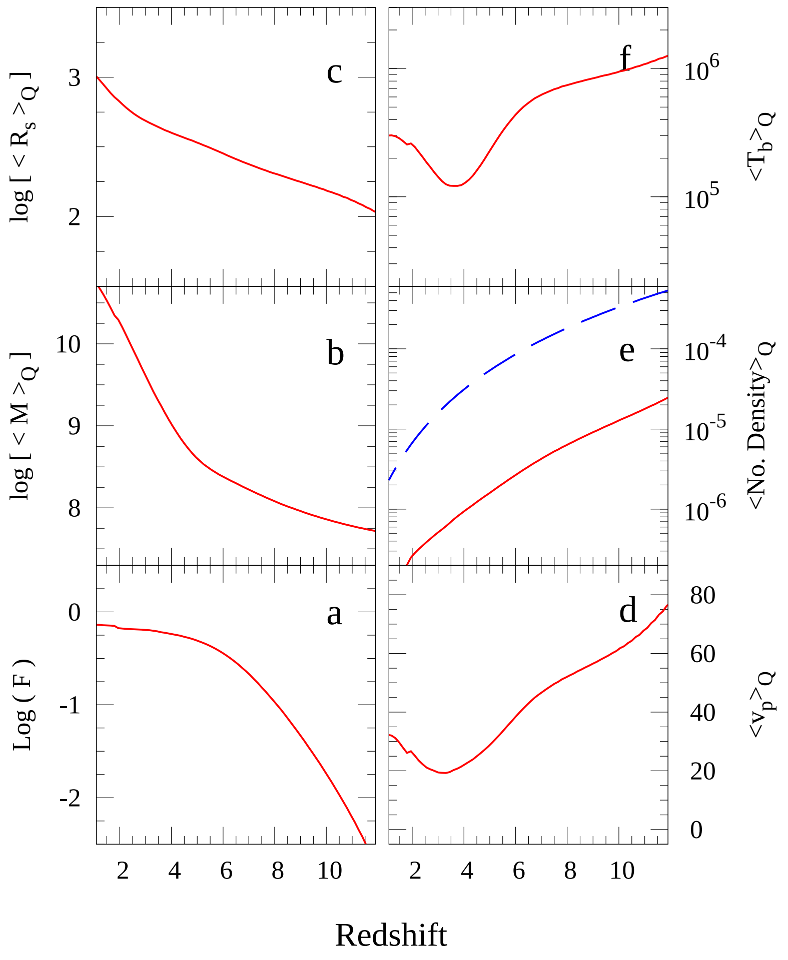
Filling factor : Reionization feedback

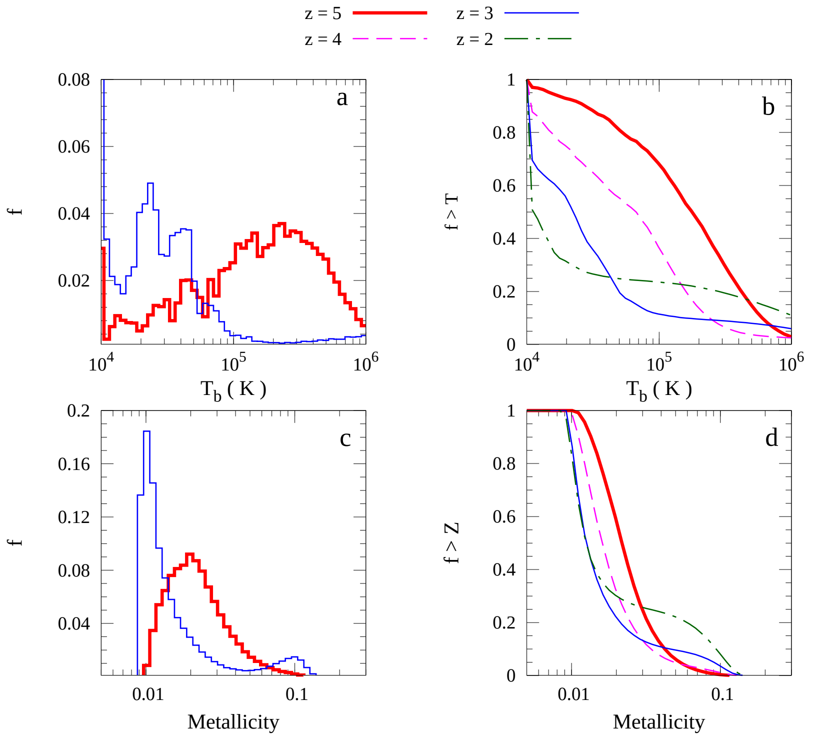


Global metallicity

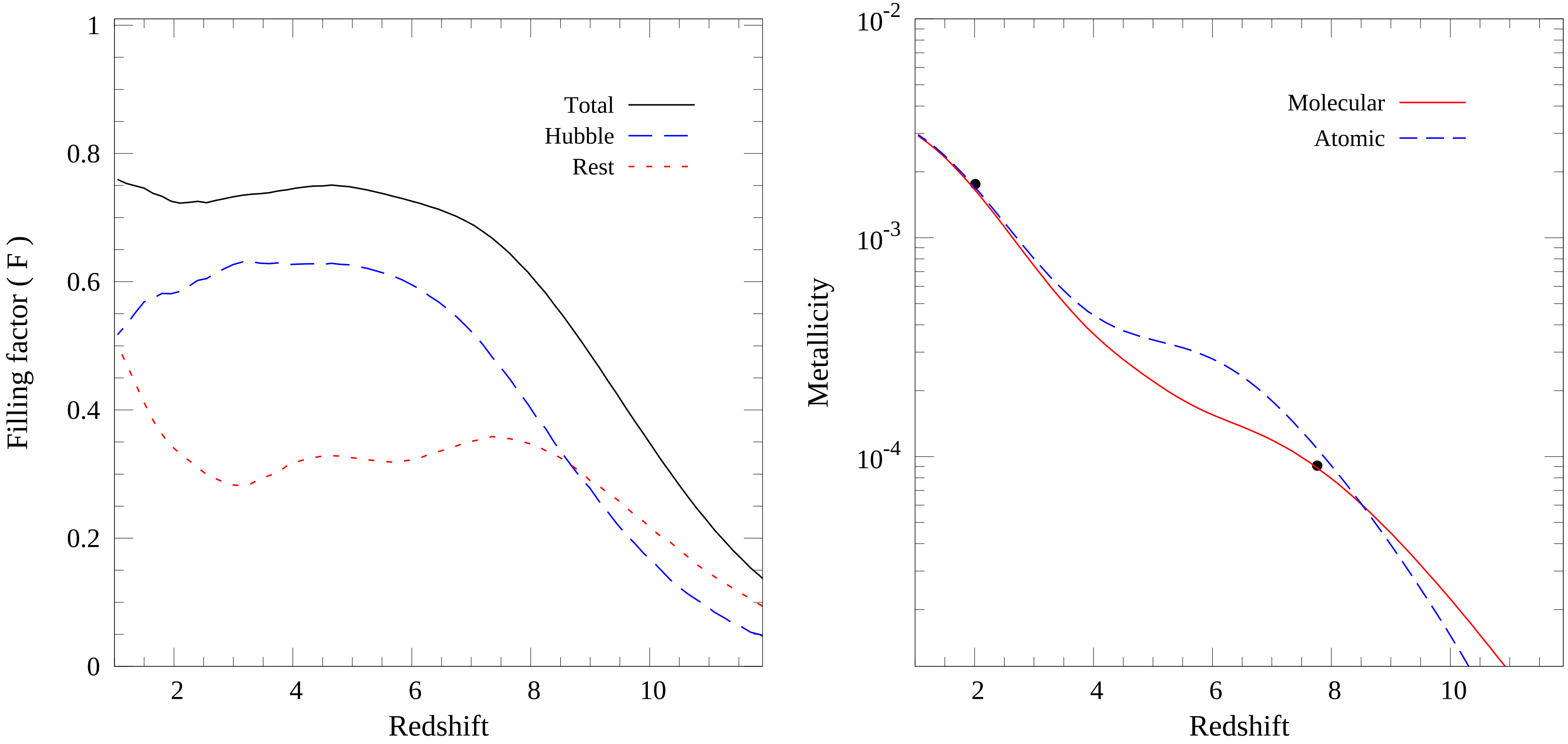


Global average properties and PDFs



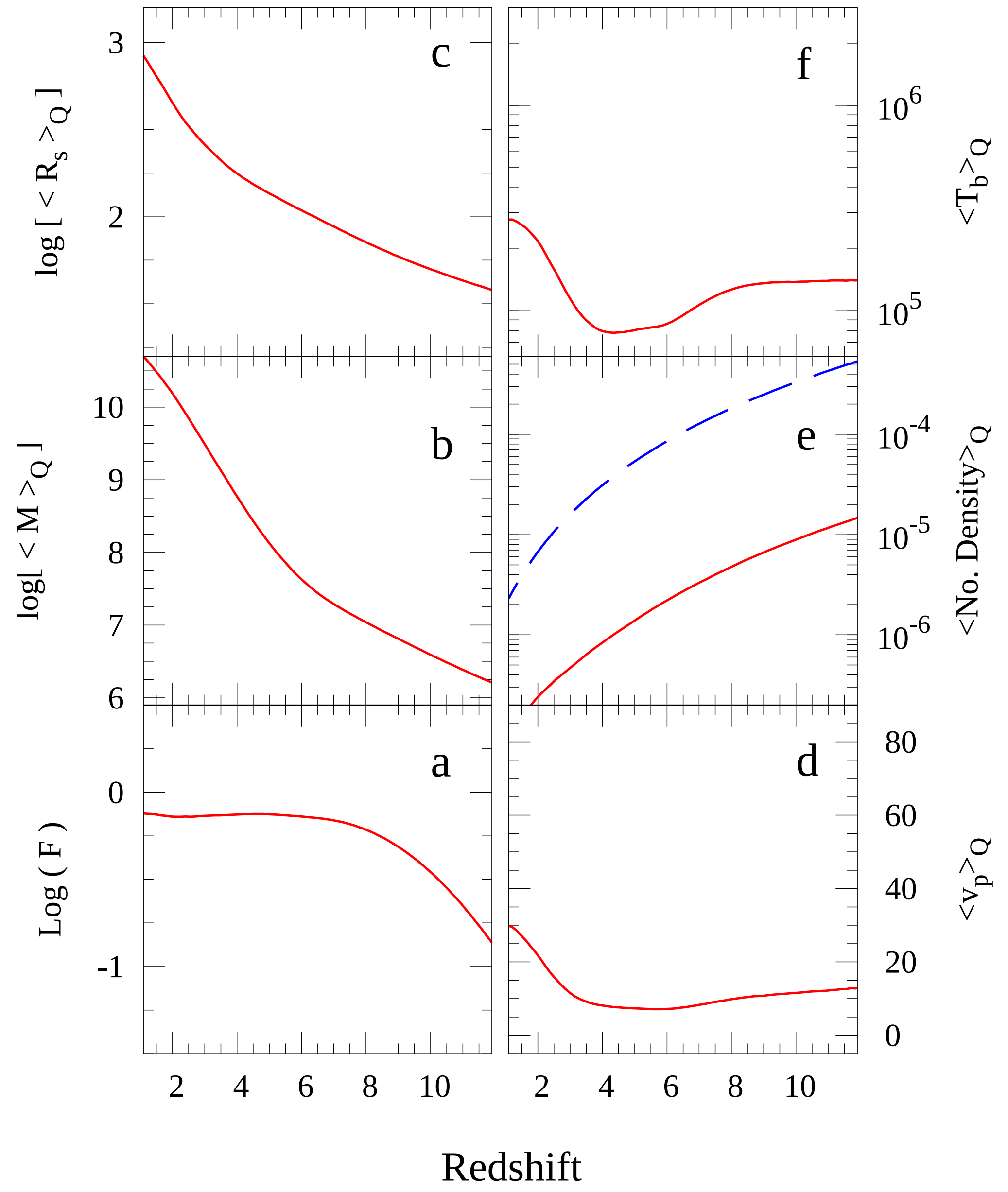


Adding Molecular cooled halos

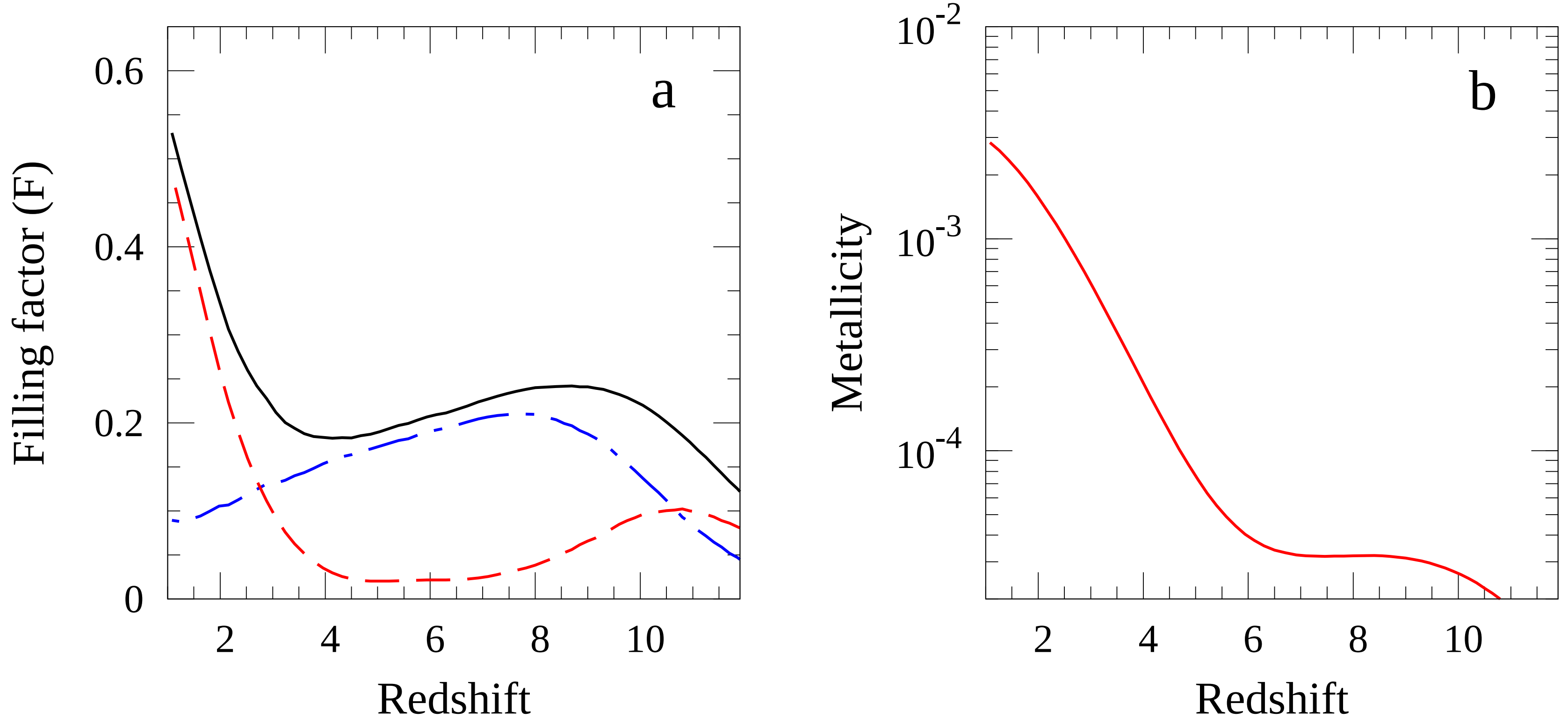


- Significant filling of IGM with outflows by $z \sim 8$ at $Z \sim 10^{-4} Z_\odot$
- Possibly without perturbing the Lyman-α forest

Molecular cooling model: averages



Filling factor : Top-heavy



Conclusions

- Outflows generically escape from low $M < 10^9\ M_\odot$ halos.
- Flow accelerates within halo, unstable to R-T instability.
- Outflows travel well into the IGM and can carry metals there.
- Significant volume filled with outflows.
- Metallicity floor obtained is $\lesssim 10^{-3}\ Z_\odot$
- Reionization feedback has signifcant effects
- Atomic cooling models may perturb Ly-α forest dynamically
- Molecular cooled halos can spread metals into IGM at high z
- But need normal mode of star formation not top heavy mode.

Questions / Suggestions

Instability of the shell

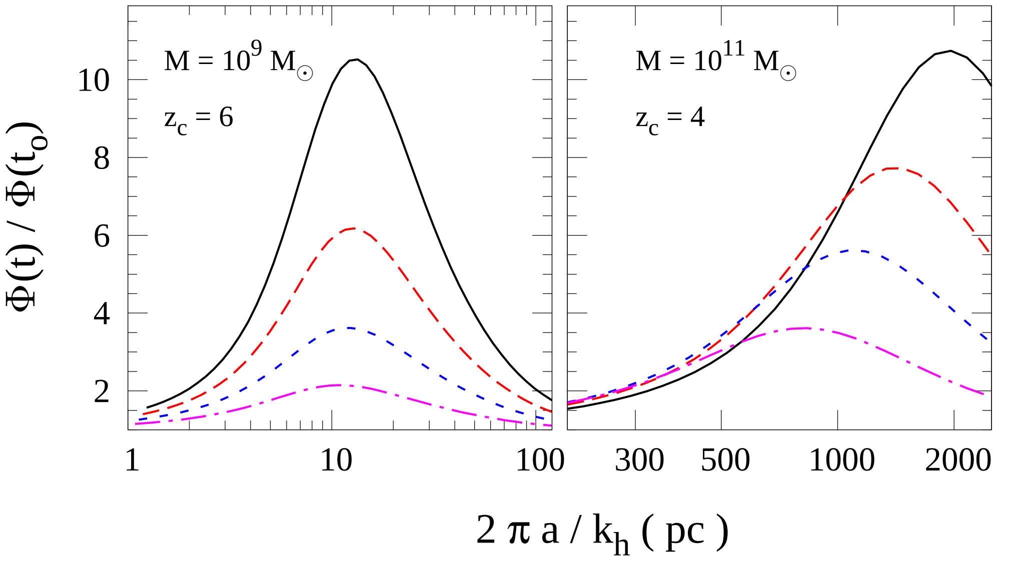
- Accelerating shell can break due to Rayleigh-Taylor instability which help in mixing
- The growth of perturbation

$$\frac{\mathrm{d}\dot{\phi}}{\mathrm{d}t} + \left(2\frac{\dot{a}}{a} + \frac{\nu k_h^2}{a^2}\right)\dot{\phi} - \omega^2\phi = 0$$

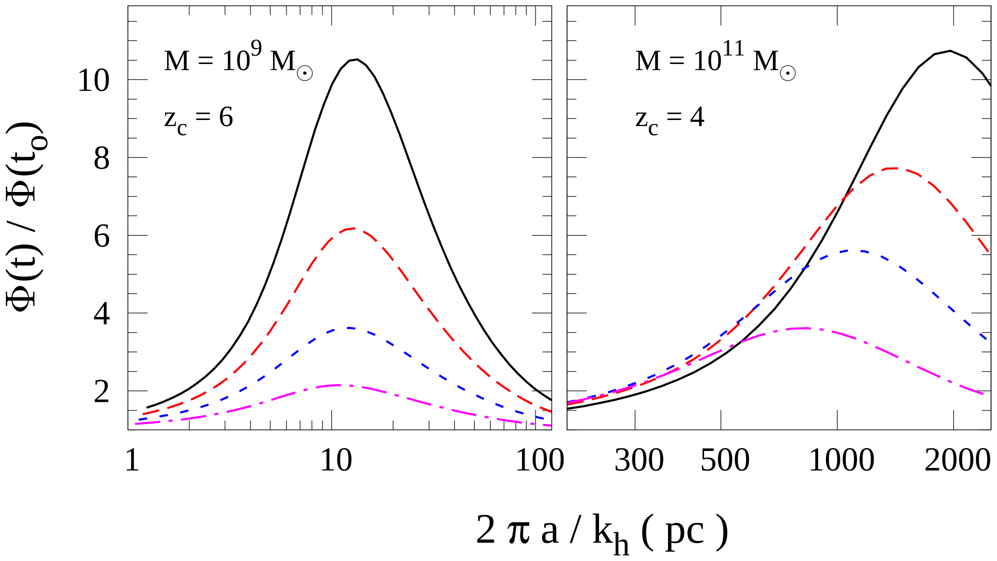
$$\omega^2 = \left[|g| + \ddot{R}_s\right]\frac{k_h}{a}\frac{\rho_s - \rho_b}{\rho_s - \rho_b}$$

- The shell is likely to fragment when ϕ is large

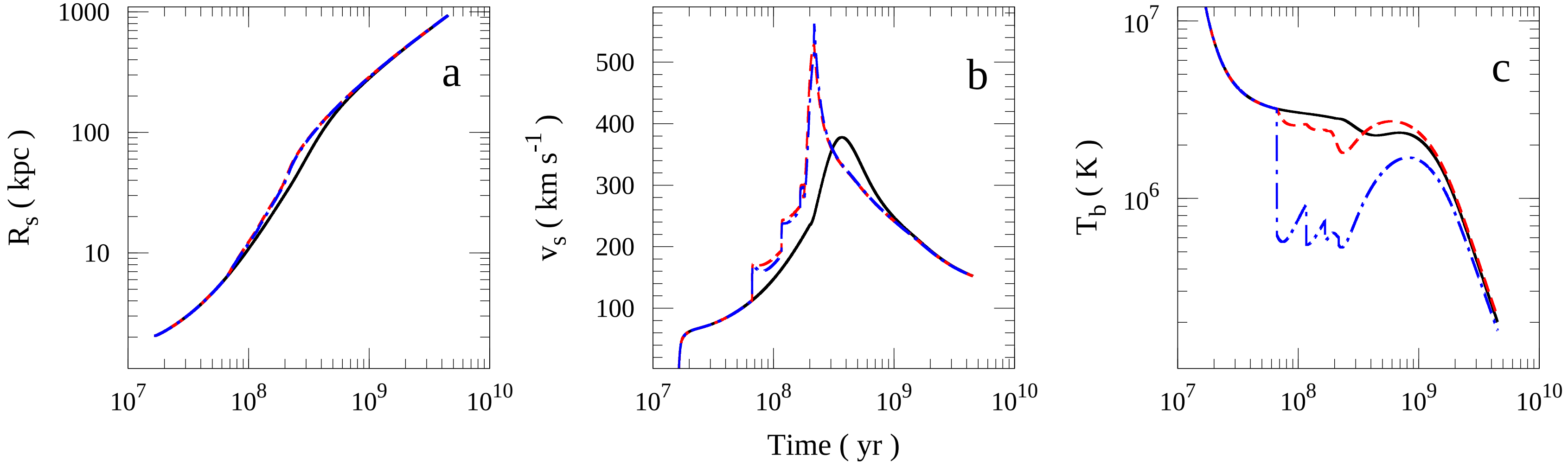
RT instability



RT instability



$M = 10^{11}\ M_\odot$, $z_c = 4$



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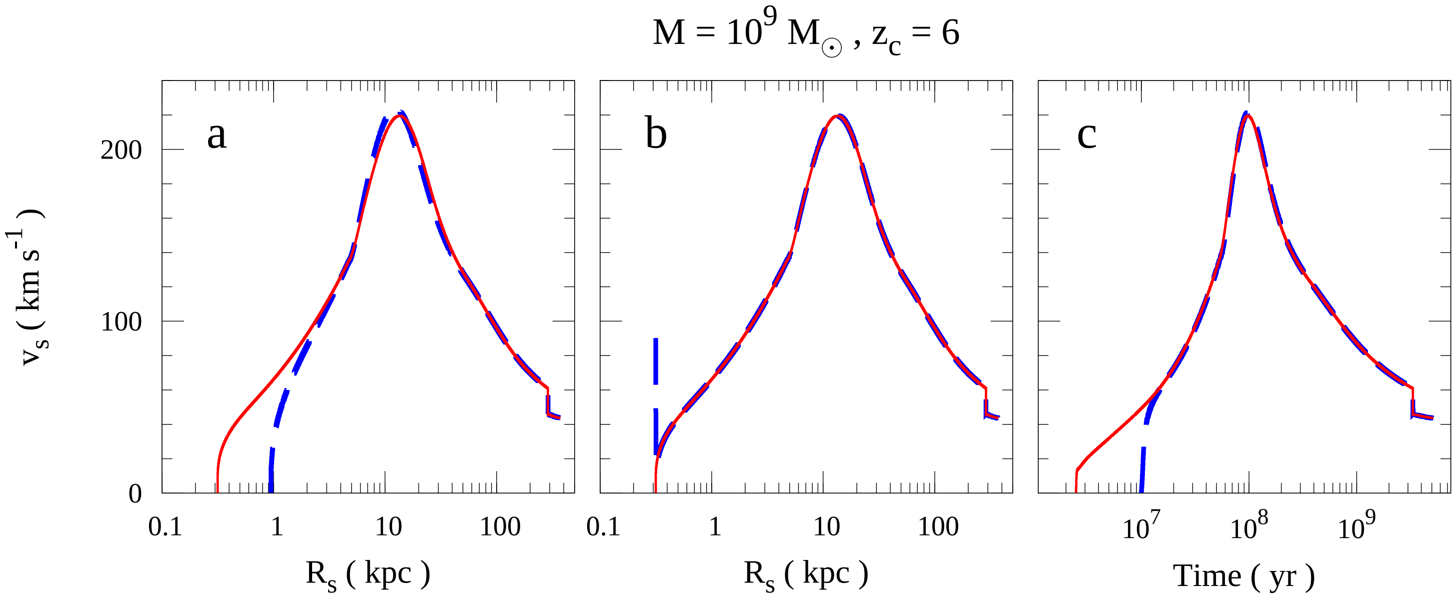
Effect of initial conditions



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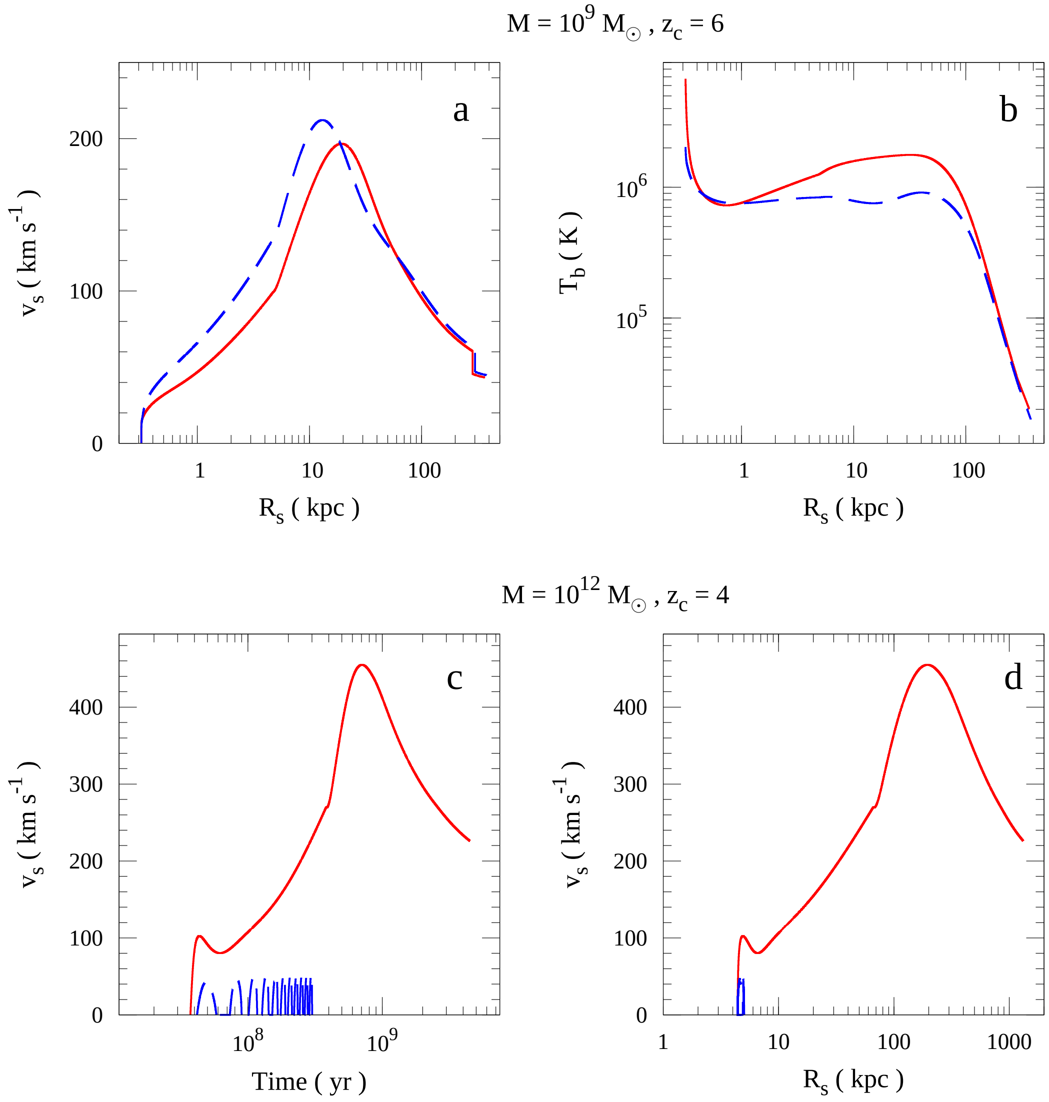
Effect of mass loading

$\eta = 0.3$ $\eta = 1$



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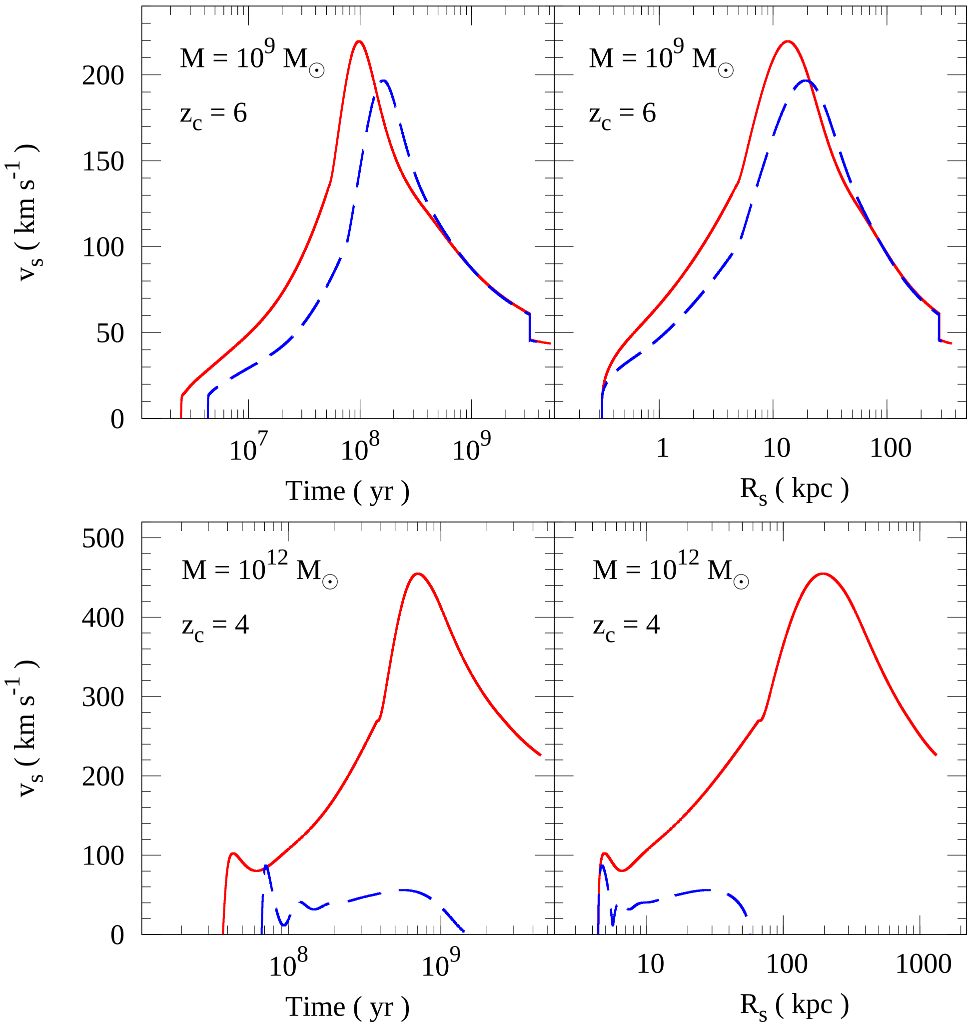
Halo mass fraction



$f_h = 0.1$ $f_h = 0.3$

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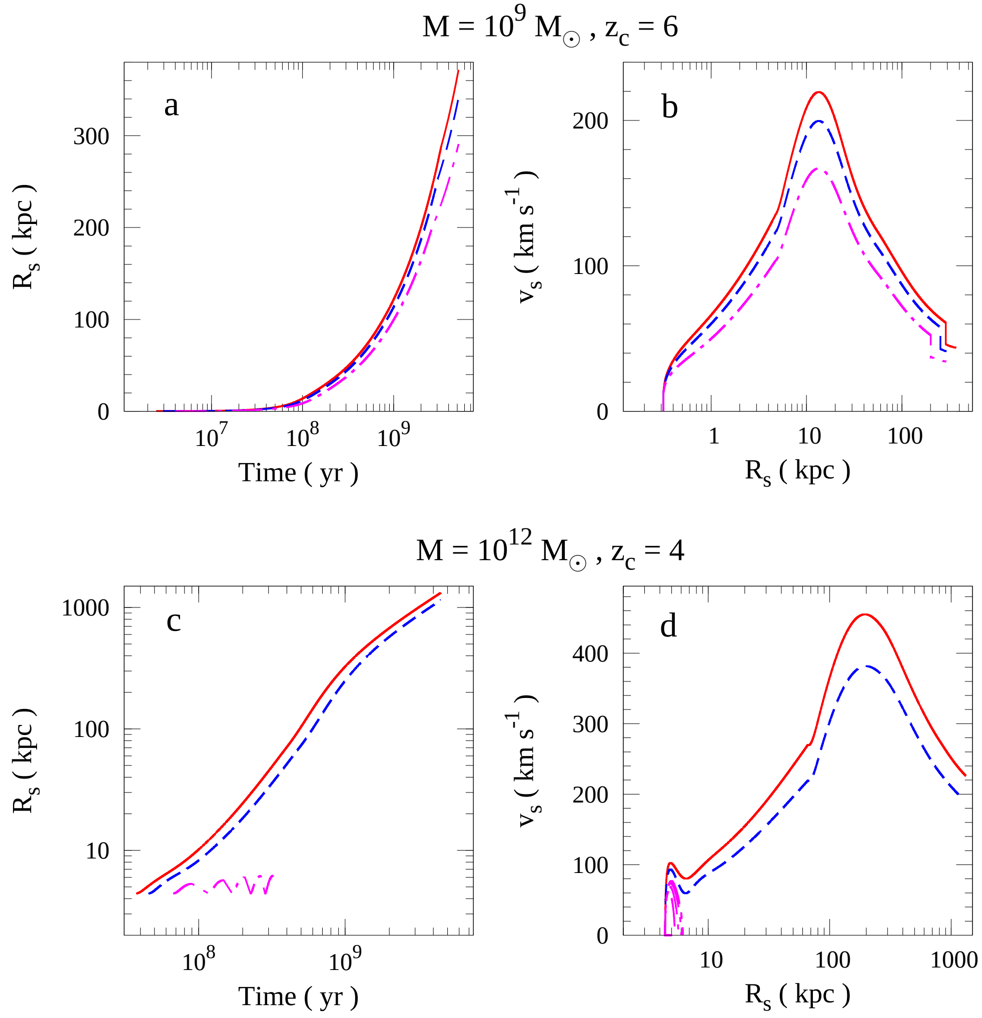
Effect of IMF

Lower mass cut-off of $1M_\odot, 0.5M_\odot, 0.1M_\odot$



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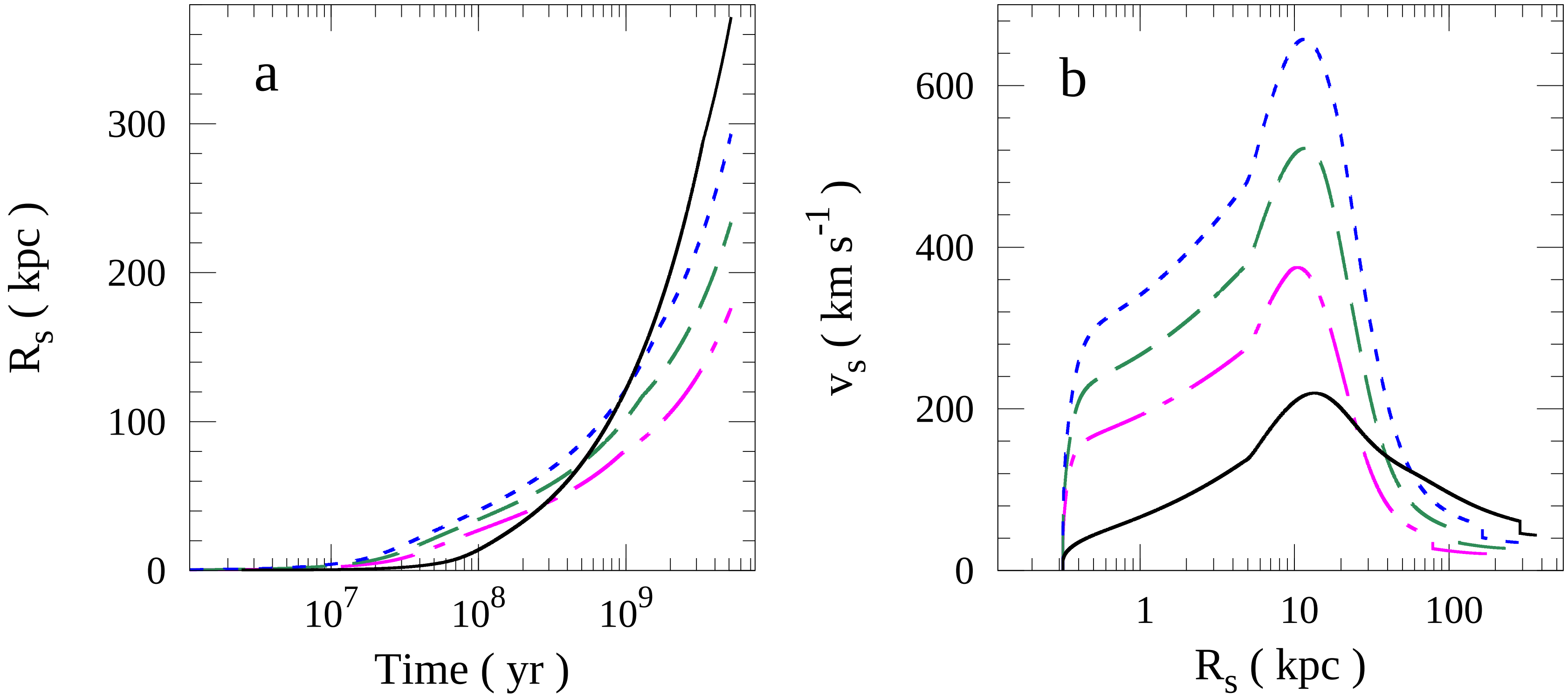
Continuous vs burst

$M = 10^9\ M_\odot\ ,\ z_c = 6$



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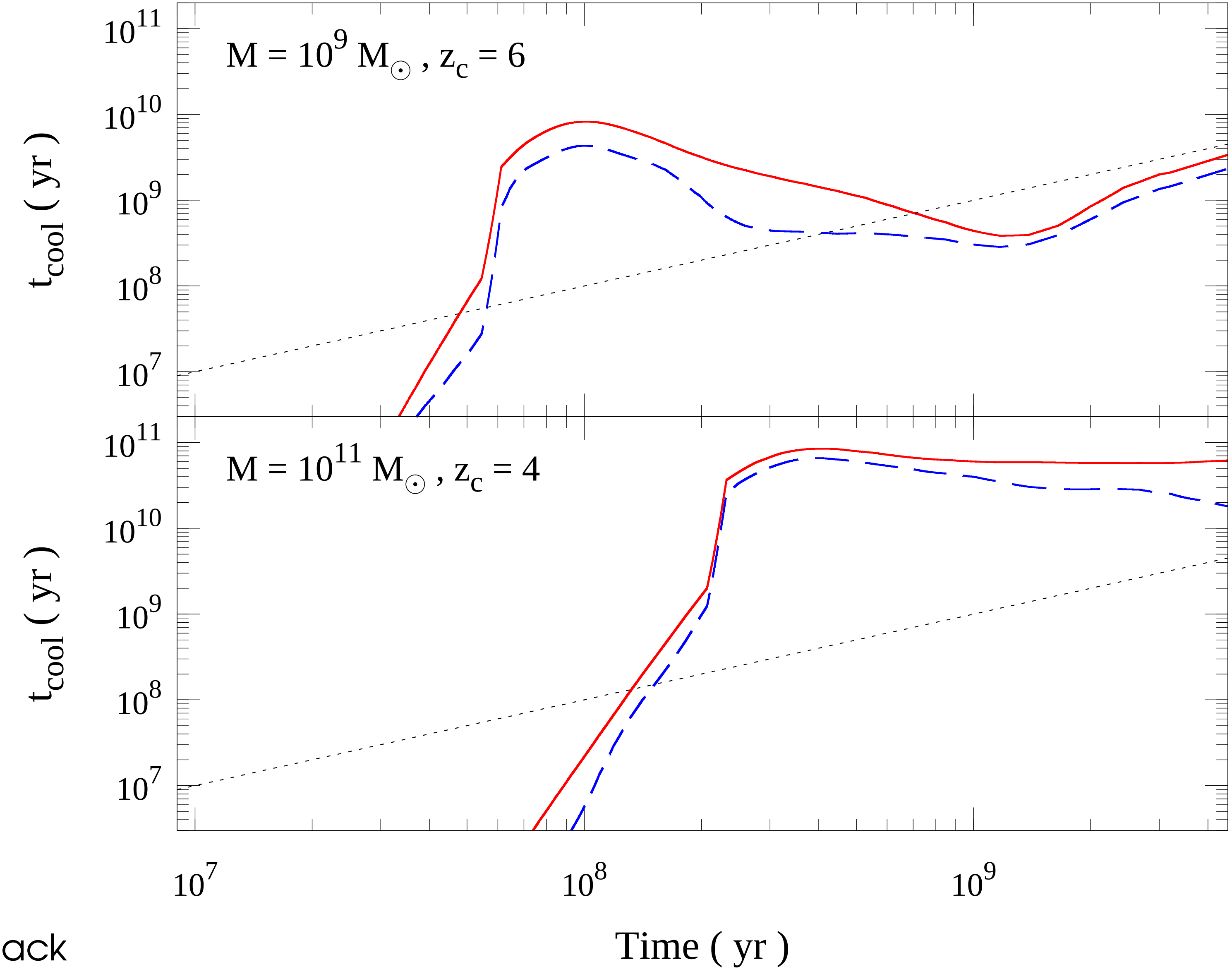
Cooling time



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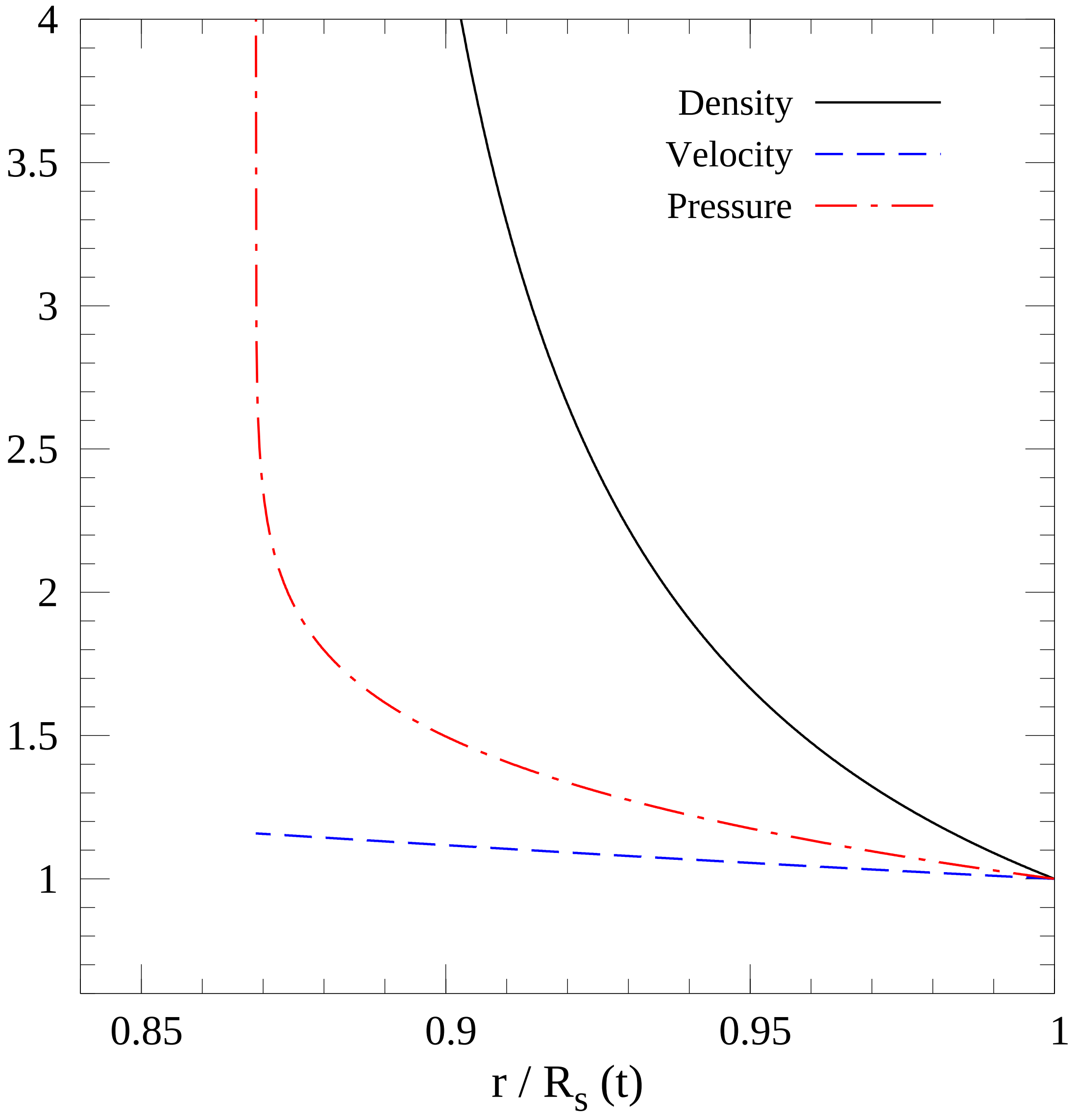
Structure of the shell



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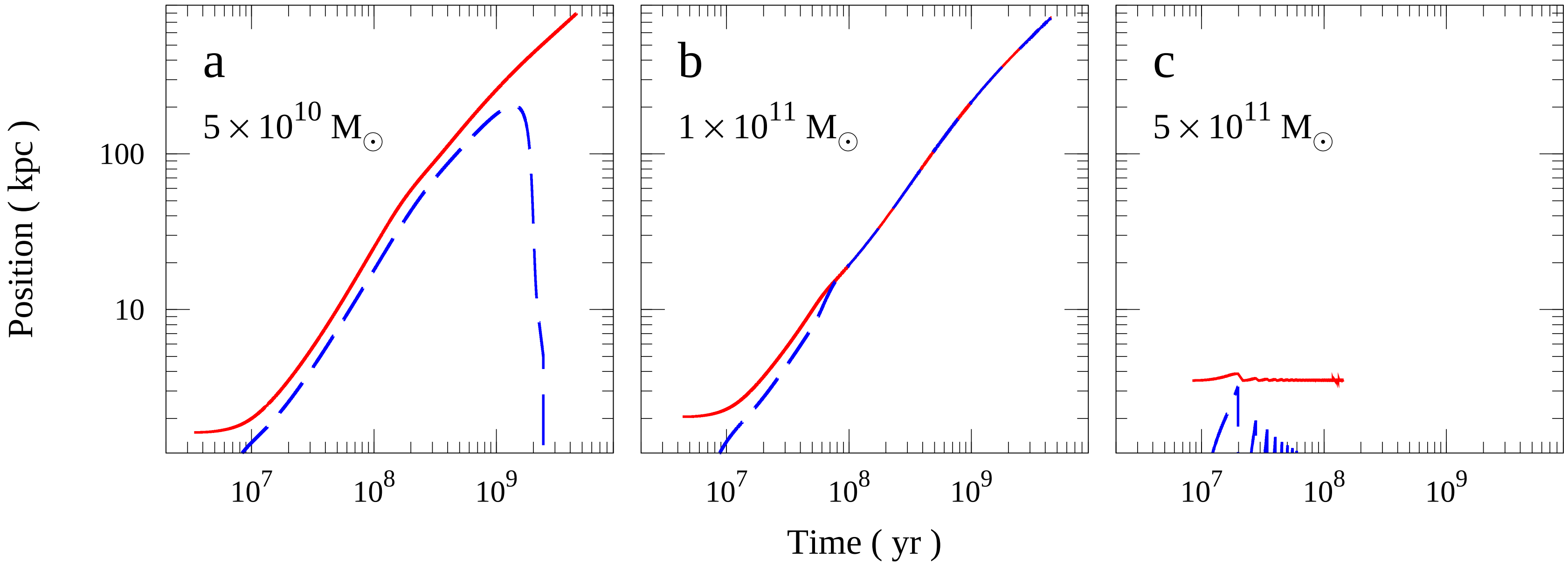
Momentum driven winds

$f_* = 0.25,\ \kappa = 0.5,\ \eta = 2.5,\ f_h = 0.02,\ \varepsilon = 0.15,\ Z = 0.03\ Z_\odot,\ z_c = 4$



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