Cosmic ray driven outflows from high redshift gaaxies

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Plan

- Why winds from high z galaxies?
  - Observations of high-z Lyman-break galaxies and DLAs show evidence for outflows?
  - Metals associated with Ly-α forest.

    Evidence for metals in the IGM? How did they get there?

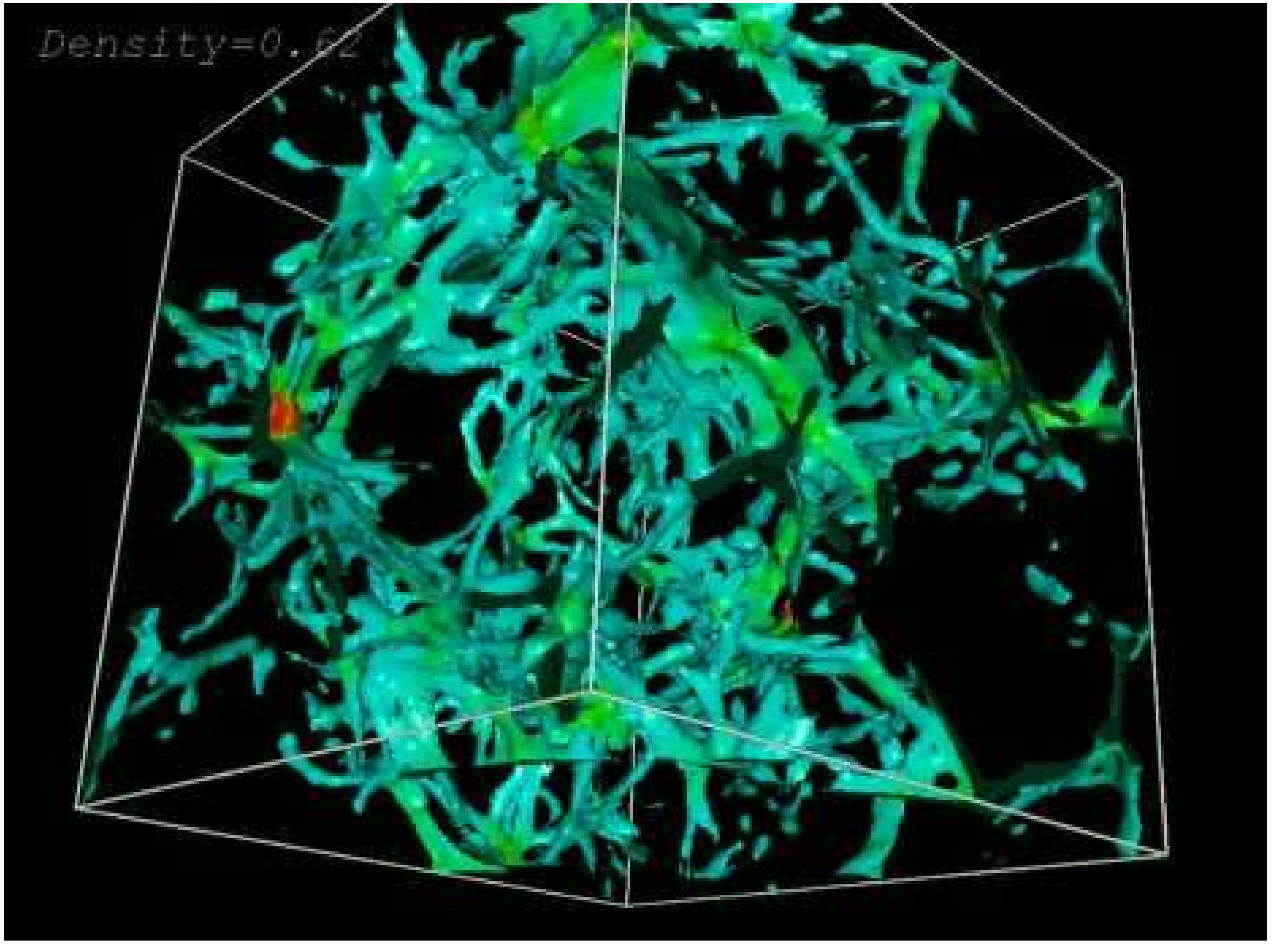
    Will also inject Turbulence, B fields, CRs in IGM
  - Feedback due to outflows important to explain galaxy LF?
- Why Cosmic ray driven winds?
- Analytical estimates and numerical examples
- Conclusions

Samui, Subramanian, Srianand, MNRAS, 2010 (In Press)

Outflow generators

Courtesy: Antonella Maselli

Ly-α forest from IGM

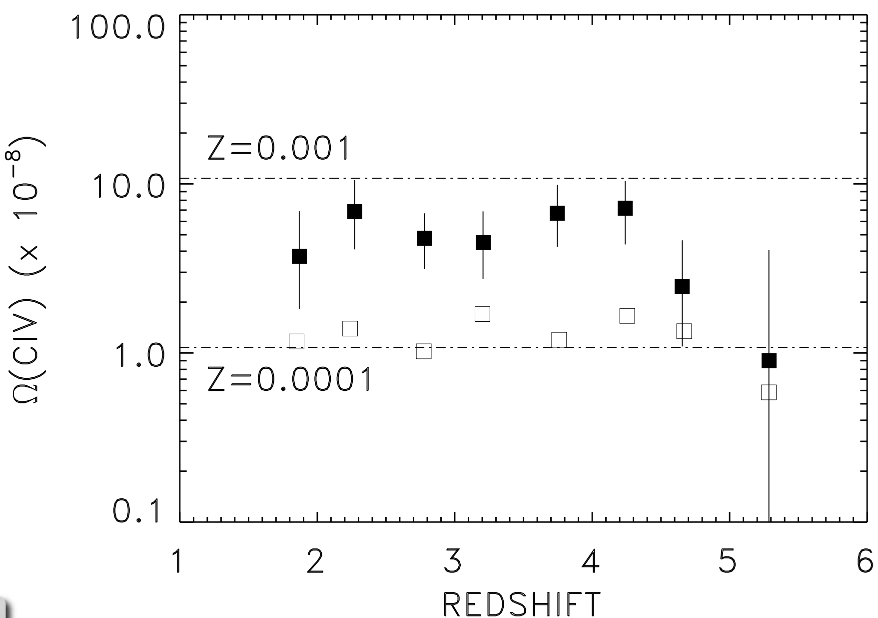


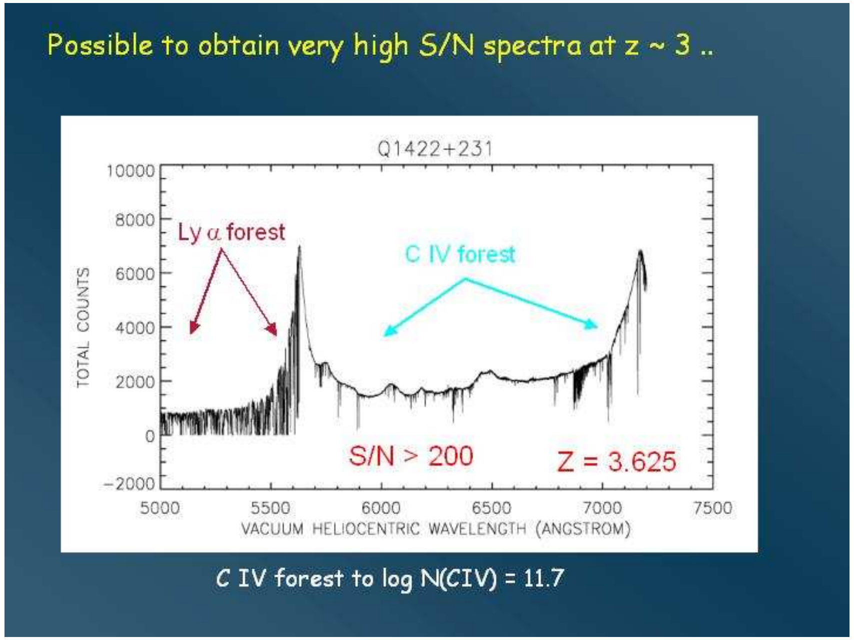
J. Shalf, Y. Zhang et al, 1998

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?
- Will also inject Turbulence, B fields, CRs in IGM

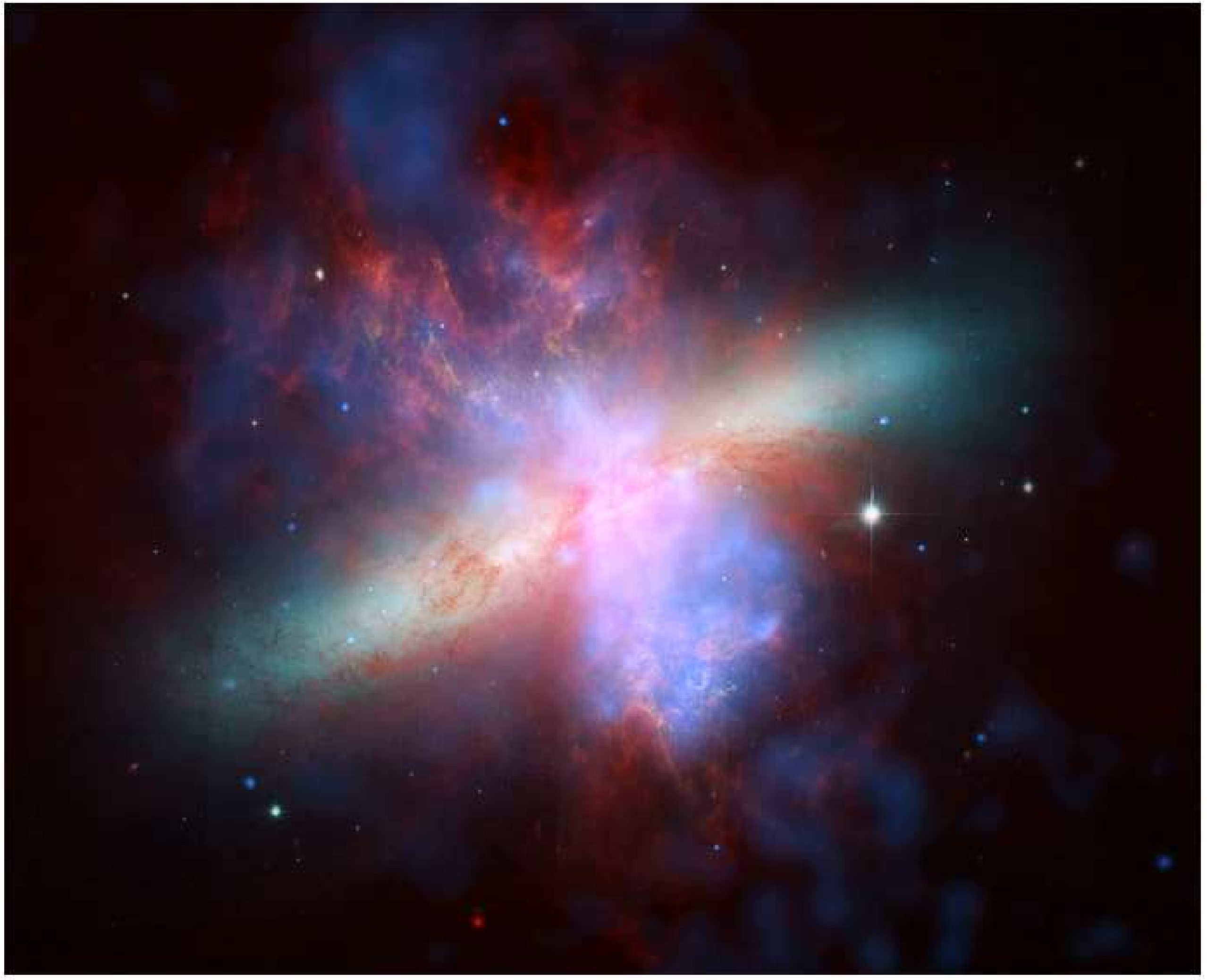
Songaila, ApJ, 561, L153, 2001





Songaila, 2004, KITP talk (CIV 1548,1550)

Outflow from Starburst galaxy M82



NASA website

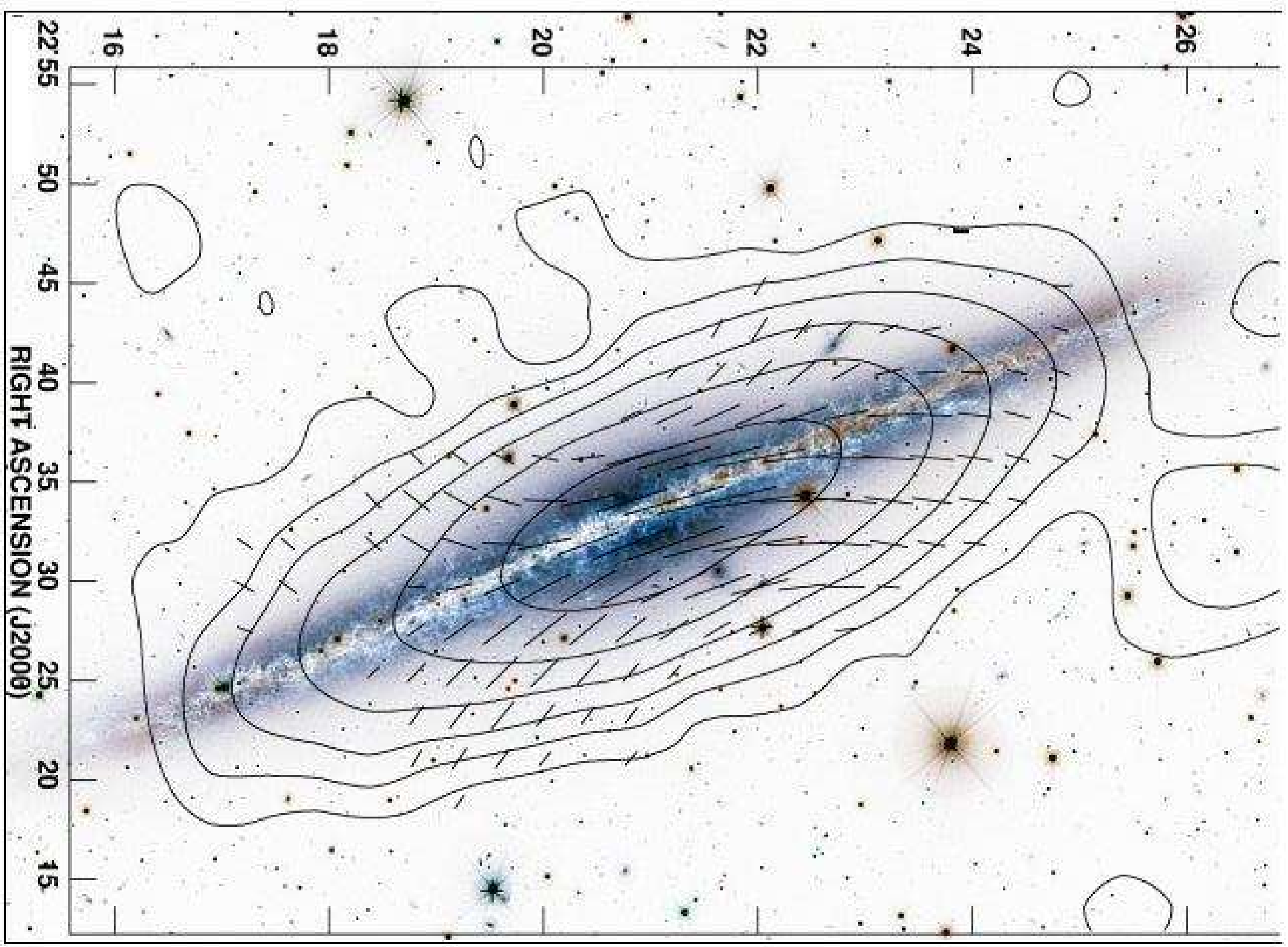
Why Cosmic ray driven winds?

- Cosmic rays (protons) accelerated in Supernovae shocks, with $> 10\%$ efficiency, energy density ~ 1 ev cm^{-3} in galaxy
- They gyrate around magnetic field lines, excite MHD Alfvén waves via streaming instability. And "resonantly" scatter of the same waves
- This process leads to isotropy, and temporary confinement of CRs in Galaxy
- The waves then transfer momentum and energy to thermal gas
- Force excerted: $-\nabla P_c$, where $P_c \approx U_c/3$ is CR pressure
- Energy transferred to gas via waves $|\mathbf{v}_A \cdot \nabla P_c|$, $\mathbf{v}_A$ is Alfvén velocity Work done against CR pressure $-\mathbf{v} \cdot \nabla P_c$

Why Cosmic ray driven winds?

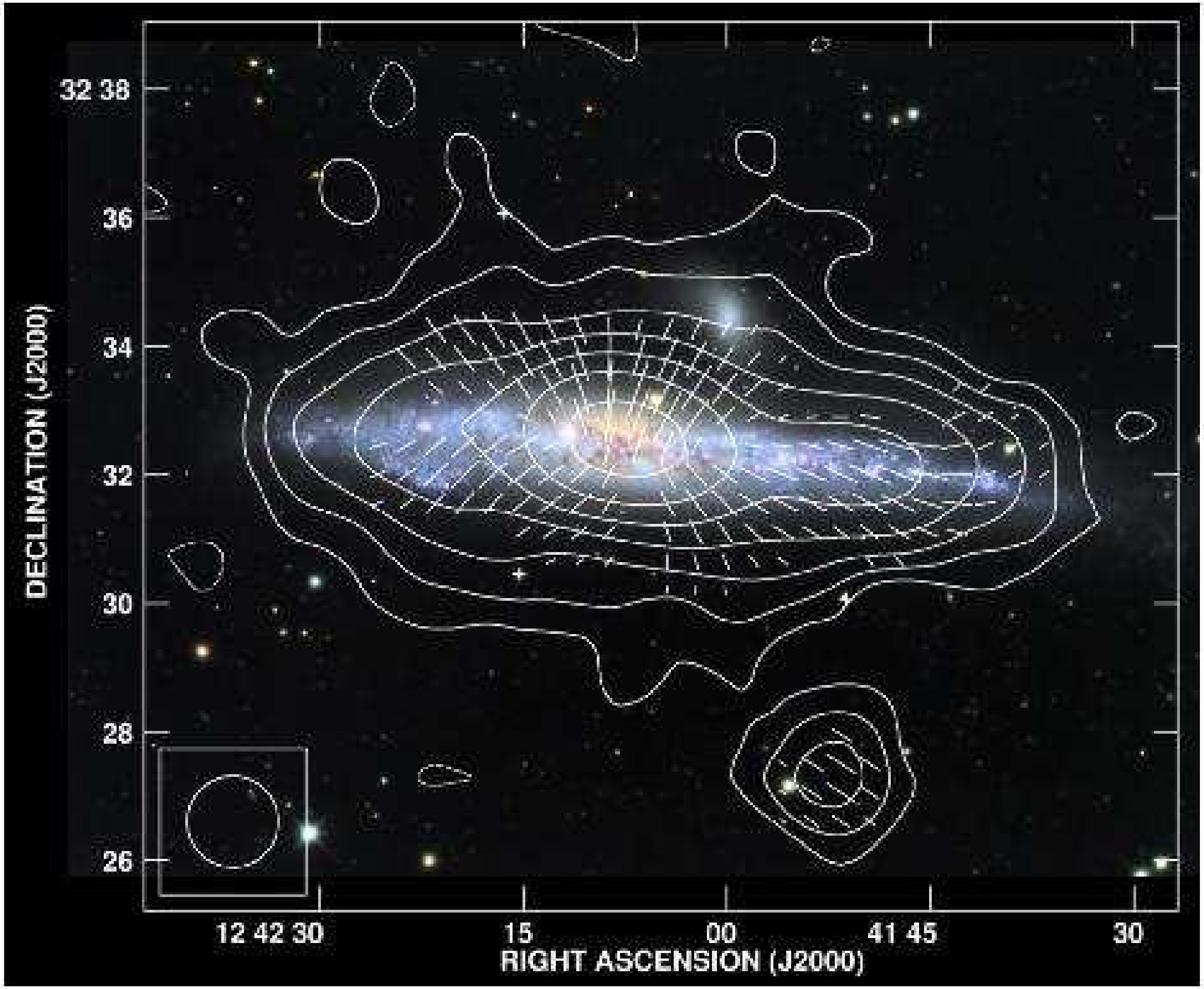
- In galaxy CR pressure comparable to other pressures
- As CRs escape they can push gas out of the galaxy
- Can be ubiquitous, even if no thermally driven winds
- Thermal wind in $\gamma = 5/3$ gas only possible if energy/momentum input region extends to the critical "sonic" point
- But CRs can naturally provide the driving even if sources (SN) confined to regions within critical point
- CRs can drive wind even if thermal energy completely lost!
- Can operate even in 'normal' galaxies, like ours (Breitschwerdt et al, 1987,91,93, Everett et al, 2009,2010)

B fields and CRs in galaxy NGC 891



Krause, 2009; Radio: MPifr, Optical: CFHT

B fie



NGC 4631, Krause, 2009; Copyright: MPifr

Steady CR driven wind

- **Equations for steady CR driven flows**

$$\rho v r^2 = q = \text{constant}; \qquad \rho v \frac{dv}{dr} = -\frac{dP}{dr} - \frac{dP_c}{dr} - \rho \frac{GM(r)}{r^2}$$

$$\frac{1}{r^2}\frac{d}{dr}\left[\rho v r^2 \left(\frac{v^2}{2} + \frac{5}{2}\frac{P}{\rho}\right)\right] = -\rho v \frac{GM(r)}{r^2} - (v + v_A)\frac{dP_c}{dr}$$

$$\frac{1}{r^2}\frac{d}{dr}\left[4P_c r^2 (v + v_A)\right] = (v + v_A)\frac{dP_c}{dr}$$

- **Here $v_A = B(r)/\sqrt{4\pi\rho}$ and we assume $Br^2 = \text{constant}$**

- **Can add energy+CR equations integrate to get:**

$$\frac{1}{2}qv^2 + \frac{5}{2}Pvr^2 - \frac{qGM}{F(c)r}\ln\left(1 + \frac{cr}{r_{vir}}\right) + 4P_c r^2 (v + v_A) = C_e$$

- **As $r \to \infty$, $(4\pi q)(v_\infty^2/2) = 4\pi C_e$, the asymptotic wind luminosity**

Mass outflow rate

- **Leads to the wind equation with "effective" sound speed** c_*

$$\frac{dv}{dr} = \frac{(2v/r)\left[1 - (GM(r)/2rc_*^2)\right]}{\left[(v^2/c_*^2) - 1\right]}; \quad c_*^2 = \frac{5}{3}\frac{P_g}{\rho} + \frac{4}{3}\frac{P_c}{\rho}\frac{(v + v_A/2)(v - 2v_A/3)}{v(v + v_A)}$$

- **Critical point when** $v(l) = c_*(l) = \sqrt{GM(l)/2l} = V_c/\sqrt{2}$

- **Asymptotic velocity** $v_\infty = FV_c/\sqrt{2}$, **with** $F/\sqrt{2} \sim 1$

- **Let luminosity** L_0 **be input by SNe and fraction** f **end up as wind kinetic luminosity**

- **As** $r \to \infty$**, the energy outflow rate**

$$4\pi C_e = (4\pi q)v_\infty^2/2 = \tfrac{1}{2}\dot{M}_w v_\infty^2 = fL_0 = f(\nu \dot{M}_{SF})(\epsilon_w E_{SNe}).$$

Mass outflow rate

- **So the mass outflow rate is :**

$$\dot{M}_w = 4\pi q = \frac{4fL_0}{F^2V_c^2} = \frac{4f\nu\dot{M}_{SF}\epsilon_w E_{SNe}}{F^2V_c^2}.$$

- **The mass loading factor η_w is**

$$\eta_w = \frac{\dot{M}_w}{\dot{M}_{\rm SF}} \approx \frac{4f}{F^2}\left(\frac{\epsilon_w}{0.1}\right)\left(\frac{220\ {\rm kms}^{-1}}{V_c}\right)^2\left(\frac{100M_\odot}{\nu^{-1}}\right)$$

- **To fix factor f one needs to consider source region and match**
- **For Uniform source distribution and NFW potential get $f \sim 0.1$**
- **For our galaxy, with $f \sim 0.1$, $F \sim \sqrt{2} \to \eta_w \sim 0.2$**
- **Dwarf galaxies $\eta_w \propto v_{cir}^{-2} \gg 1$ unless efficiency is very low**
- **Feedback due to CR driven winds crucial for normal dwarfs**

Fixing output efficiency f

- **Uniform sources $r \le R$, mass injection Q, energy injection $\mathcal{L}_0$**
  $q = QR^3/3; \quad L_0 = (4/3)\pi R^3(\mathcal{L}_{th} + \mathcal{L}_{cr}) = (4/3)\pi R^3 \mathcal{L}_0$
- **Energy equation $+$ continuity across $r = R$ gives**

$$4\pi C_e = L_0 - \frac{3\pi q G M}{\mathfrak{F}(c) R}\left[2\left\{1 - \left(\frac{r_{vir}}{cR}\right)^2\right\}\ln\left(1 + \frac{cR}{r_{vir}}\right) + \left(2\frac{r_{vir}}{cR} - 1\right)\right].$$

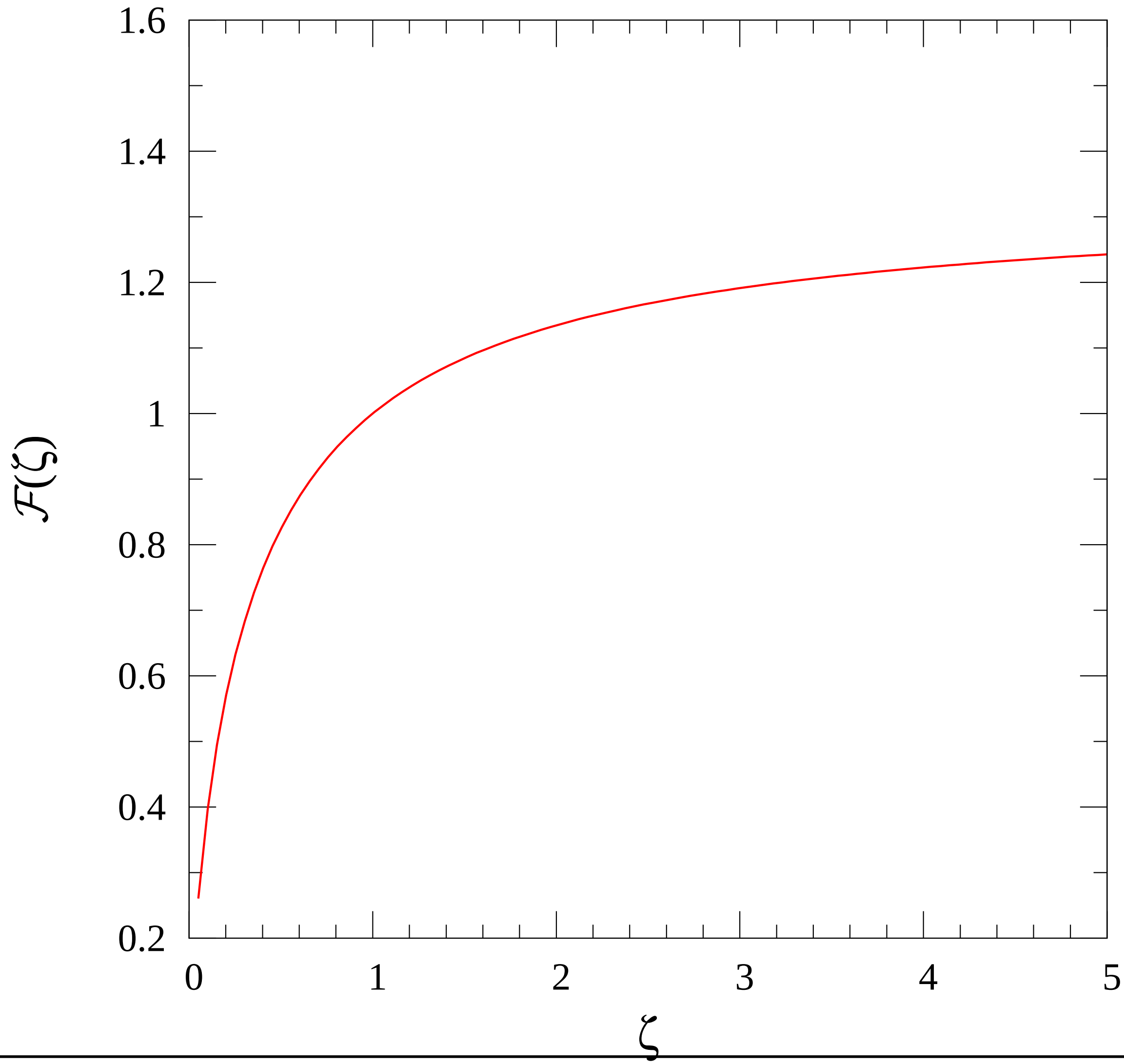
- **Need $C_e > 0$ or L_0 large enough to escape NFW potential.**
- **Use $4\pi C_e = f L_0$, $4\pi q = (4 f L_0 / F^2 V_c^2)$ to solve for f**

$$f = \left[1 + \frac{3}{2}\frac{c}{\mathfrak{F}(c)(F/\sqrt{2})^2}\frac{v_{cir}^2}{V_c^2}\mathcal{F}(\zeta)\right]^{-1}$$

- **For $R = r_{vir}/12$ and $c = 15 \rightarrow \zeta = 0.8$, then $\mathcal{F} = 0.94$, also**
  $\mathfrak{F}(c) = 1.84$ **and** $F/\sqrt{2} \approx 1$. **Then we obtain $f = 0.08$.**

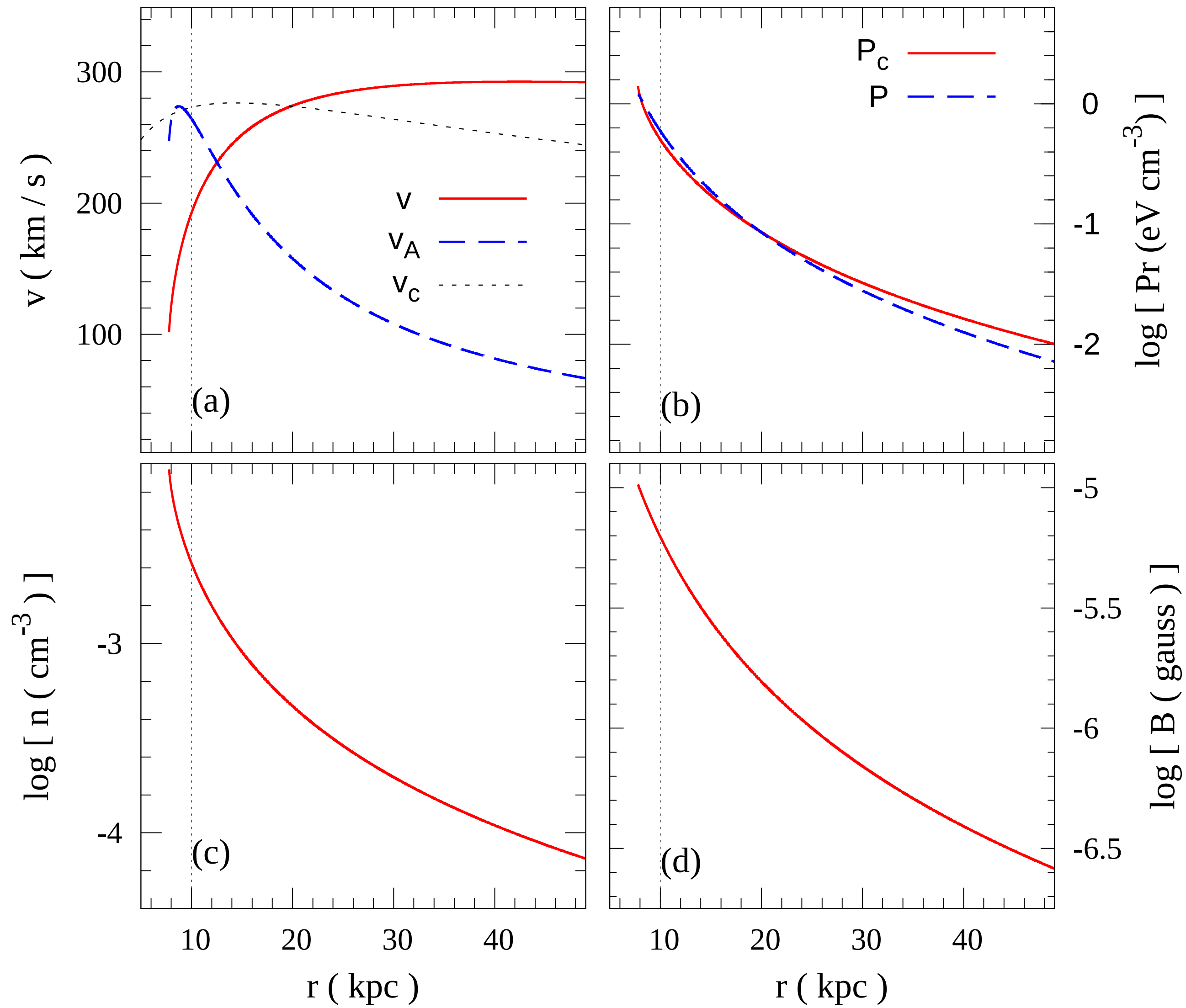
The factor $\mathcal{F}$

$$\mathcal{F}(\zeta) = 2\zeta\left(1-\zeta^2\right)\ln\left(1+\frac{1}{\zeta}\right) + \zeta\left(2\zeta-1\right); \zeta = r_{vir}/(cR)$$



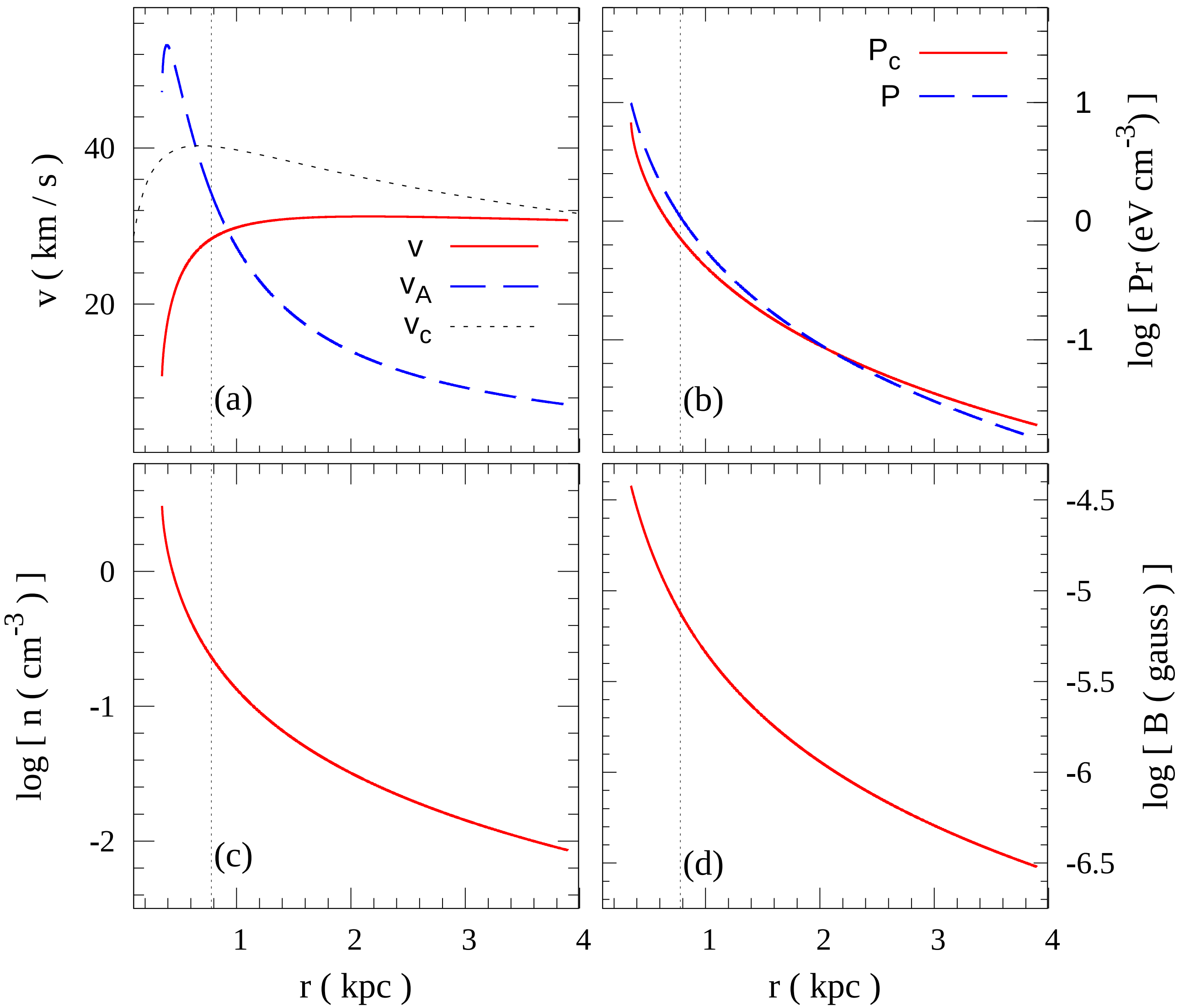
CR driven wind from $10^{12} M_\odot$ NFW halo

$L_0 = 3 \times 10^{41}$ erg s^{-1}, $\dot{M}_w = 16.2 M_\odot$ yr^{-1}, $\eta_w = 0.16$

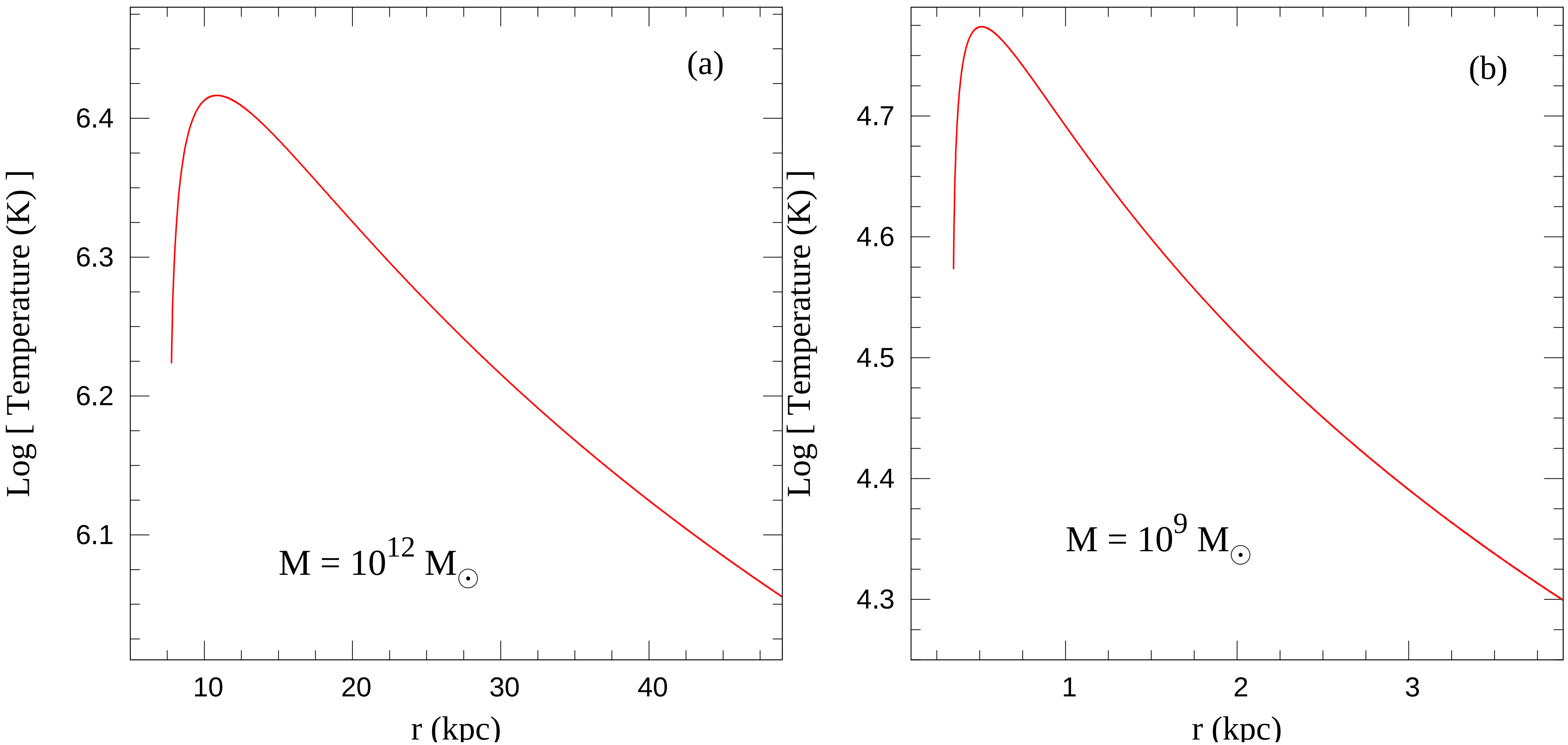


CR driven outflow from $10^9 M_\odot$ NFW halo

$L_0 = 3 \times 10^{38}$ erg s^{-1}, $\dot{M}_w = 1.27 M_\odot$ yr^{-1}, $\eta_w = 12.7$



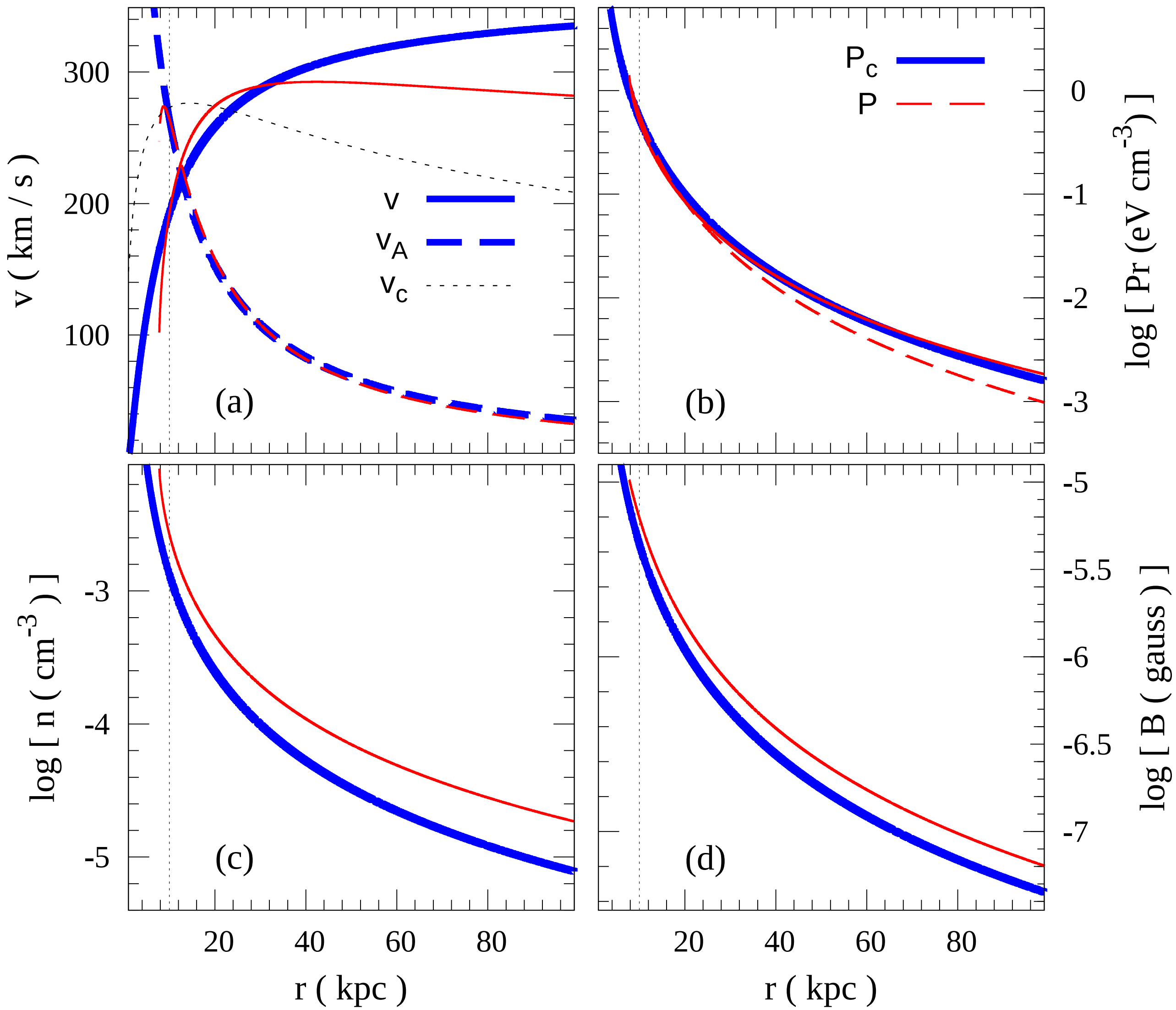
Temperature of CR driven outflow



- **Cooling time $t_c \sim 10^8 - 10^3$ yr for halos of mass $10^{12} - 10^8 M_\odot$ halos**
- **Advection time $t_d \sim 10^8$ yr**
- **Radiative cooling important for low mass galaxies**
- **Assume negligible thermal pressure for cold winds**

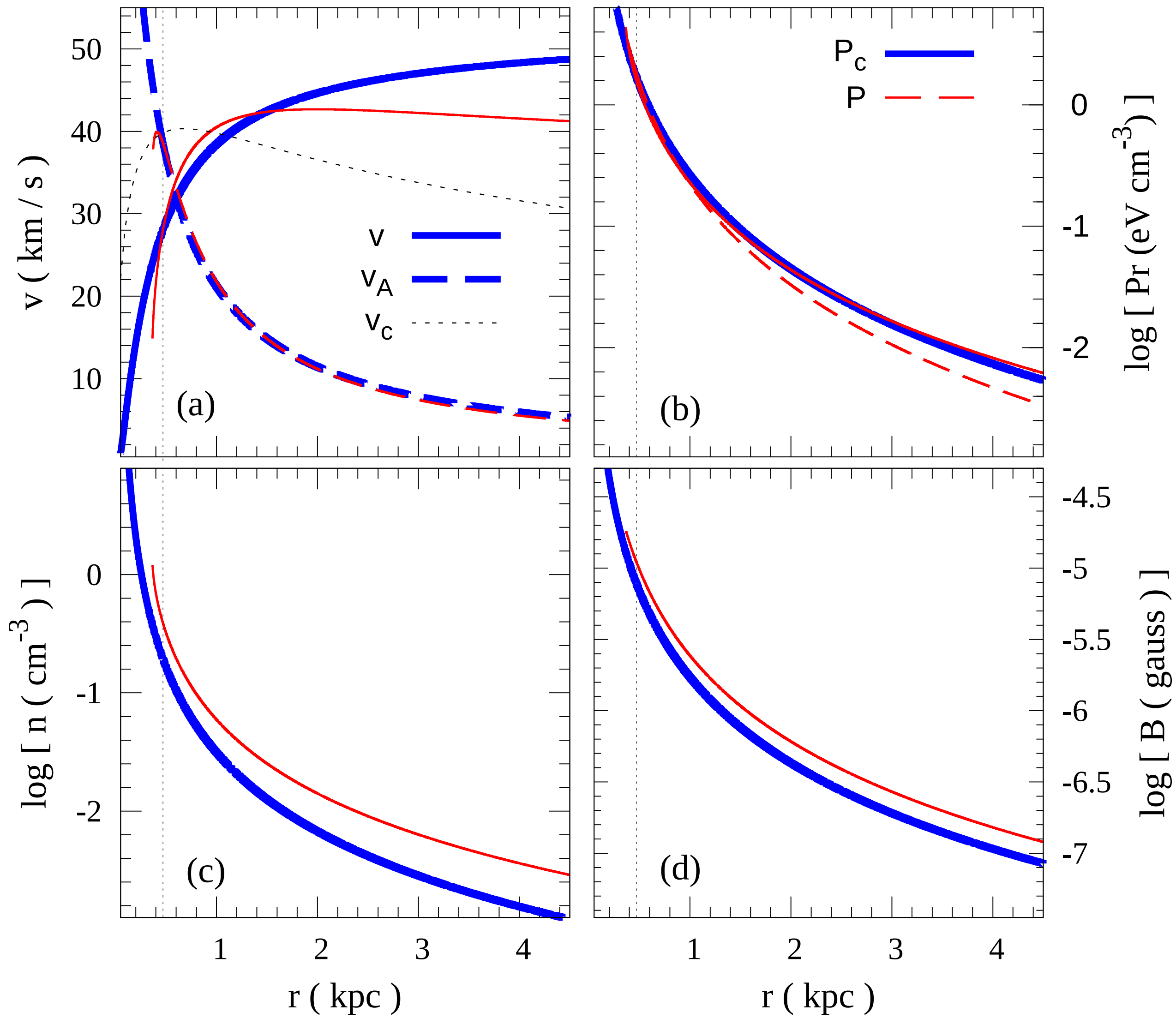
Cold CR driven wind from $10^{12} M_\odot$ halo

$L_0 = 1.5 \times 10^{41}$ erg s^{-1}, $\dot{M}_w = 8.1 M_\odot$ yr^{-1}



Cold CR driven outflow from $10^9 M_\odot$ halo

$L_0 = 1.5 \times 10^{38}$ erg s^{-1}, $\dot{M}_w = 0.38 M_\odot$ yr^{-1}



Conclusions

- CR driven winds can lead to supersonic outflows.
- Works even if energy sources (SNe) within critical point
- Needs $B \sim \mu G$, but coherence scale need not be large
- Asymptotic speeds $v_\infty \sim V_c$.
- Mass loss rate per unit SFR, $\eta_w < 0.2 - 0.5$ for massive galaxies, but much larger for dwarfs as $\eta_w \propto V_c^{-2}$.
- Strong wind cooling for dwarfs; still cold winds possible, driven by CRs, possibly with factor 2 smaller η_w.
- But does not predict strong X-ray emission from dwarfs.
- Will typically obtain in all normal star forming galaxies!
- Strong mass loss from small mass halos $\Rightarrow$ low efficiency or strong feedback, consequences to be worked out.