Cosmic ray driven winds in the Galactic environment and the cosmic ray spectrum

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Overview

- Winds in the Milky Way
- The role of CRs
- CR transport
- The role of the Galactic environment
- Dark matter halo

Importance of Galactic winds

...in galaxies

- ubiquitous (AGN, starburst galaxies, ...)
- mass loss of $\sim \mathrm{M}_\odot/\mathrm{yr}$
- flow speed $\sim 100\mathrm{km/s}$
- driven by: thermal gradients, radiation pressure, CR pressure gradients

...potentially important for the Milky Way

- galactic evolution, star formation rate
- chemical composition of ISM and IGM
- missing baryons?
- effect on the CR transport

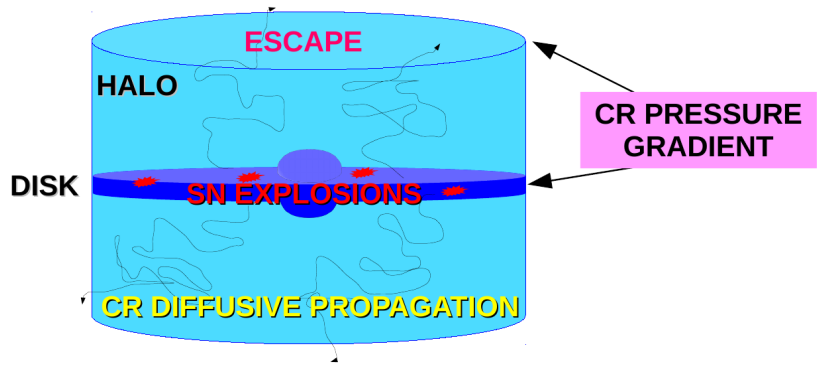
Galactic winds and the role of CRs

...observations (Miller & Bregman (2015))

- X-ray (Oxygen lines) em./abs.
- $100\,\mathrm{kpc}$, $10^6\,\mathrm{K}$
- metallicity $\sim 0.2 - 0.3$ (from the disk)
- EVIDENCE OF WINDS?

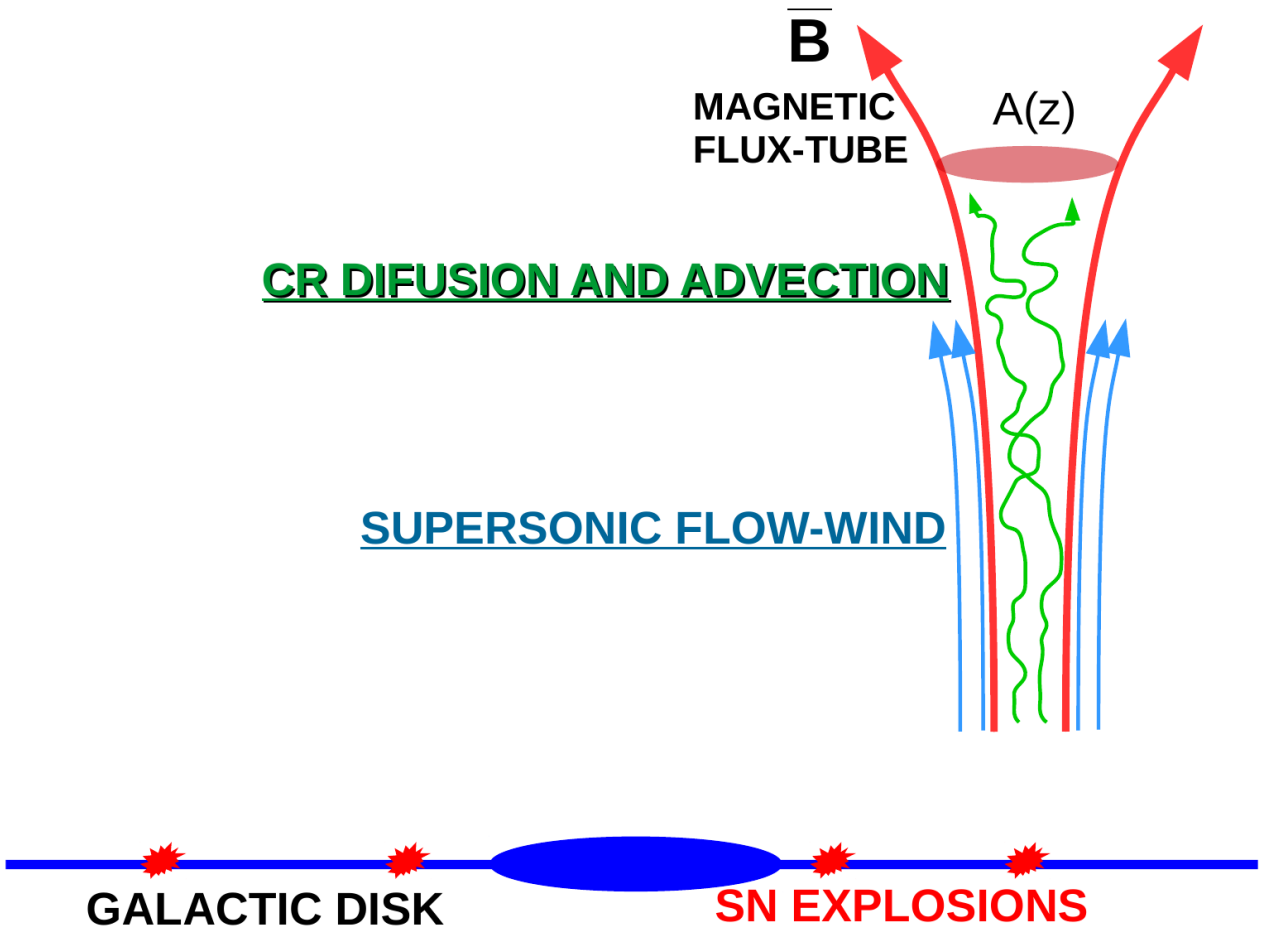
...role of CRs

- CR pressure gradient in the MW
- $\mathrm{P_{CR}} \sim \mathrm{P_{TH}} \sim \mathrm{P_{MAG}}$
- thermal and radiation pressure insufficient
- dynamical role?



Galactic Winds and the CR transport

- CRs escaping from the Galaxy can generate a Galactic wind
- winds affect the CR propagation (advection)



The CR transport equation

transport equation

$$\frac{\partial}{\partial z}\left[A\,D\frac{\partial f}{\partial z}\right] - A\,U\frac{\partial f}{\partial z} + \frac{d(A\,U)}{dz}\frac{1}{3}\frac{\partial f}{\partial \ln p} + A\,Q = 0,$$

- DIFFUSION: CR streaming instability saturated through NLLD

$$\Gamma_{\rm CR} = \frac{16\pi^2}{3}\frac{v_A}{\mathcal{F}B^2}\left[p^4 v(p)\left|\frac{\partial f}{\partial z}\right|\right]_{p=p_{res}}$$

$$\Gamma_{\rm D} = (2c_k)^{-3/2} k v_A \mathcal{F}^{1/2}$$

$$D(z,p) = \frac{1}{3}\frac{v(p) r_L(z,p)}{\mathcal{F}(z,k_{res})}\bigg|_{k_{\rm res}=1/r_L}$$

- ADVECTION: wind + self generated Alfvén waves

The wind equation

wind hydrodynamics

$$\rho u A = \text{const}$$

$$AB = \text{const}$$

$$\frac{dP_g}{dz} = \gamma_g \frac{P_g}{\rho}\frac{d\rho}{dz} - (\gamma_g - 1)\frac{v_A}{u}\frac{dP_c}{dz}$$

$$\frac{dP_c}{dz} = \gamma_{eff}\frac{P_c}{\rho}\frac{2u + v_A}{2(u + v_A)}\frac{d\rho}{dz}$$

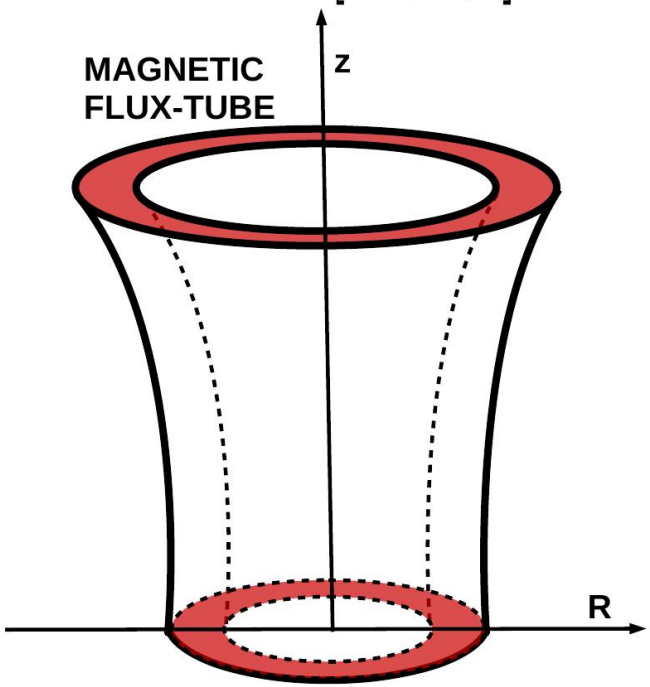
$$c_*^2 = \gamma_g \frac{P_g}{\rho} + \gamma_{eff}\frac{P_c}{\rho}\left[1 - (\gamma_g - 1)\frac{v_A}{u}\right]\frac{2u + v_A}{2(u + v_A)}$$

$$\frac{\gamma_{eff}}{\gamma_{eff} - 1} = \frac{\gamma_c}{\gamma_c - 1} - \frac{\overline{D}}{(\gamma_c - 1)(u + v_A)P_c}\frac{dP_c}{dz}$$

wind equation

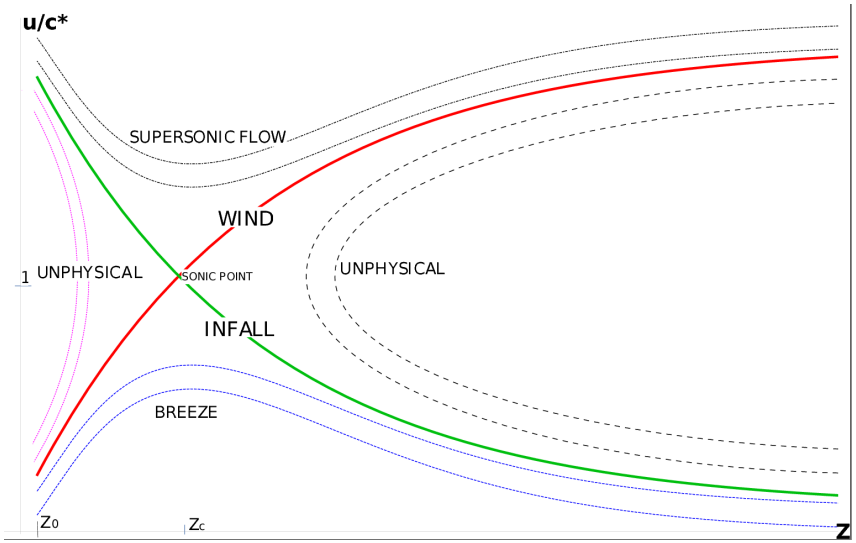
$$\frac{du}{dz} = u\frac{c_*^2\frac{1}{A}\frac{dA}{dz} - \frac{d\Phi}{dz}}{u^2 - c_*^2}$$

$$A(z) = A_0\left[1 + \left(\frac{z}{Z_b}\right)^{\alpha}\right]$$



The wind equation

- at the wind base $\mathrm{n_0}$, $\mathrm{T_0}$, $\mathrm{P_{c0}}$, $\mathrm{B_0}$ are given by the Galactic environment
- need to determine the **wind launching velocity** u_0
- crucial role of the **Galactic gravitational potential**, in particular of the Dark Matter halo



- critical point of the wind equation
- NUM=0, DEN=0
- smooth transition to **supersonic flow**

The effect of the Galactic environment

the wind launching depends on:

- input parameters at the wind base (n, T, B, $\mathrm{P_c}$)
- flux-tube geometry
- gravitational potential (bulge, disk, Dark Matter halo)

constraint from observations

- hot ionized medium (Ferriere (2011))
- observations (Miller & Bregman (2015))
- dependence on the position in the Galaxy

wind solution exists for:

- closed intervals of the input parameters
- small n and g, large T and P_c: non stationary outflows...
- large n and g, small T and P_c: not enough energy for outflow...
- stationary non transonic flows, non stationary flows...

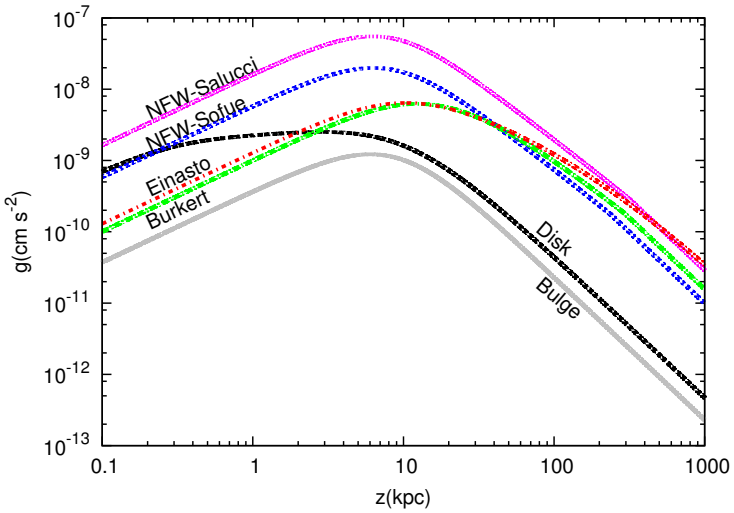
The effect of the DM halo

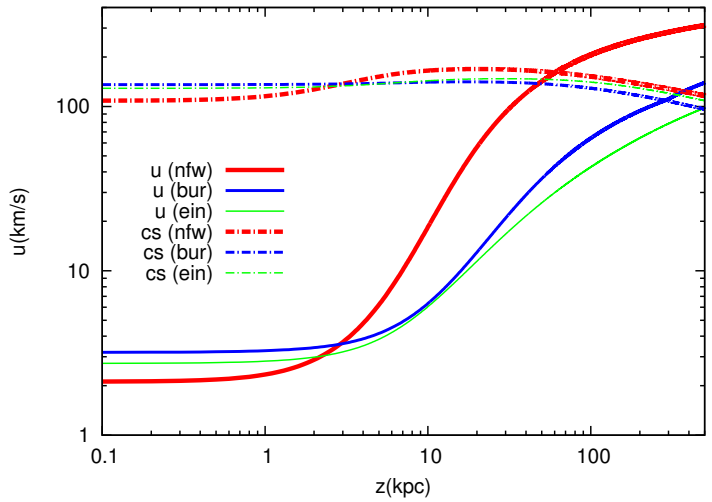
- **Bulge-Disk**

- NFW:
  $(\rho_0 = 1.06 \times 10^7\ \mathrm{M}_\odot\ \mathrm{kpc}^{-3};\ r_c = 12.0\ \mathrm{kpc})$ (Sofue (2012))
  $(\rho_0 = 1.3 \times 10^7\ \mathrm{M}_\odot\ \mathrm{kpc}^{-3};\ r_c = 16.0\ \mathrm{kpc})$ (Salucci (2013))
- Burkert:
  $(\rho_0 = 4.13 \times 10^7\ \mathrm{M}_\odot\ \mathrm{kpc}^{-3};\ r_c = 9.3\ \mathrm{kpc})$ (Salucci (2013))
- Einasto:
  $(\rho_0 = 3.5 \times 10^{11}\ \mathrm{M}_\odot\ \mathrm{kpc}^{-3};\ r_c = 6.7 \times 10^{-6}\ \mathrm{kpc},\ \alpha = 0.17)$ (Bernal (2012))

DM density at the Sun position in the range $0.2 - 0.4\ \mathrm{GeV/cm}^3$

The effect of the DM halo





wind launching possible...

for environmental parameters in agreement with observation

environmental parameters- Sun position

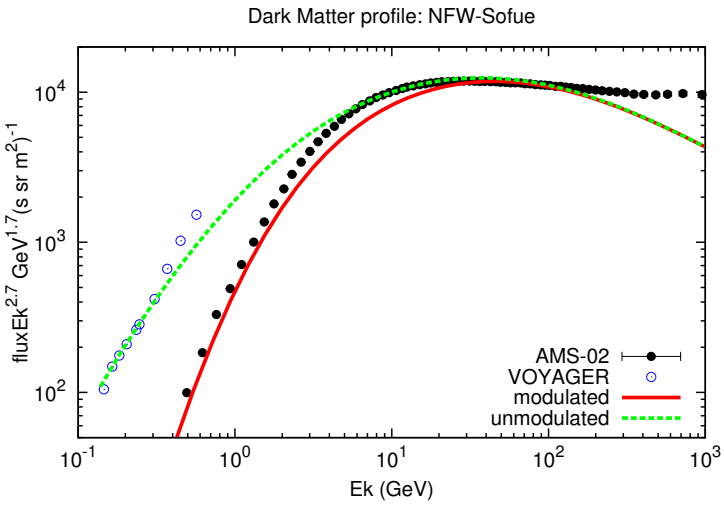
$$n_0 = 0.006\mathrm{cm}^{-3}$$

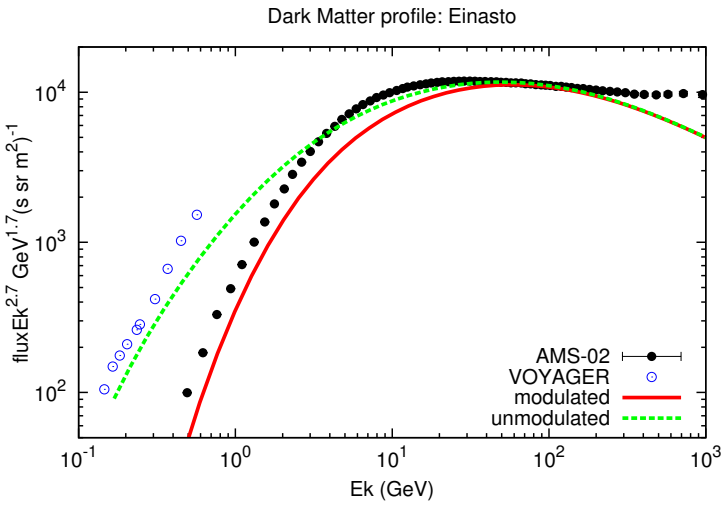
$$T_0 = 2 \times 10^6 \mathrm{K}$$

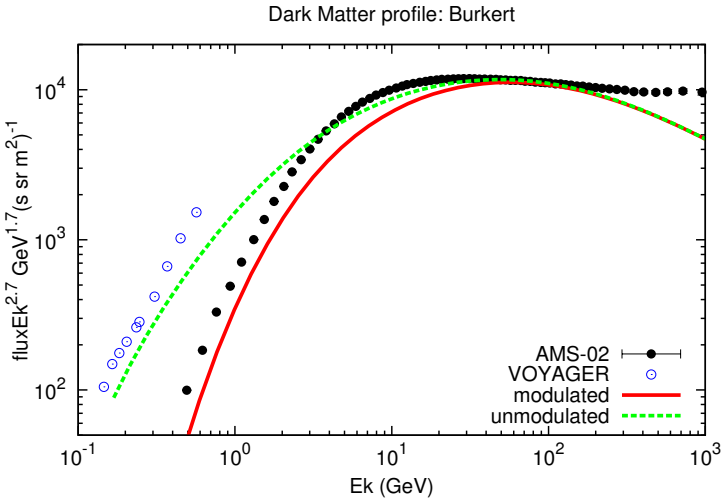
$$P_{c0} = 4 \times 10^{-13} \mathrm{erg/cm}^3$$

$$B_0 = 1\mu\mathrm{G}$$

The effect of the DM halo







complex interplay between the wind and CRs
important role of Galactic environment
important role of the DM halo

Conclusions

- CR (together with thermal) pressure gradients can generate a Galactic wind
- the wind properties depend on the Galactic environment ($\mathrm{n_0}$, $\mathrm{T_0}$, $\mathrm{P_{c0}}$, $\mathrm{B_0}$) and on the Galactic gravitational potential (DM halo)
- the wind affect the CR spectrum due to advection

- observation/modelization of the Galactic environment and of the Galactic gravitational potential
- observed CR spectrum
- provides **strong constraints** on the possible existence and properties of winds in the Milky Way