COSMIC RAY INDUCED GALACTIC WINDS

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OVERVIEW

- What are Galactic winds?
- The role of CRs
- Hydrodynamics of galactic winds
- CR transport in a CR-driven wind
- Diffusive halo
- CR spectrum
- Role of the Galactic environment

WHAT ARE GALACTIC WINDS?

- Outflows from Galaxies
- (non)-stationary
- Flow subsonic near the gal. Disk
- Flow accelerated to supersonic speed by thermal, radiation, CR pressure gradients...

WINDS IN GALAXIES

- AGN, Starburst Galaxies, ...
- Mass loss $\dot{M} \simeq M_S / yr$
- Flow speed $u \simeq 100\, km/s$
- Driven by P_{TH} , P_{RAD} , P_{CR} , ...

- Galactic evolution
- Star formation rate
- Chemistry of ISM and IGM
- Missing barions

WINDS IN THE MILKY WAY

(Miller and Bregman (2015))

OBSERVED GALACTIC HALO

EVIDENCE OF WINDS?

- **X-ray em./abs.**
- **Oxygen lines**
- **Large (~ 100 kpc)**
- **Hot (~ millions K)**
- **Metallicity ~0.2-0.3**
- **From the disk**

THE ROLE OF CRs

(Ipavich (1975))

(Breitschwerdt et al. (1991))

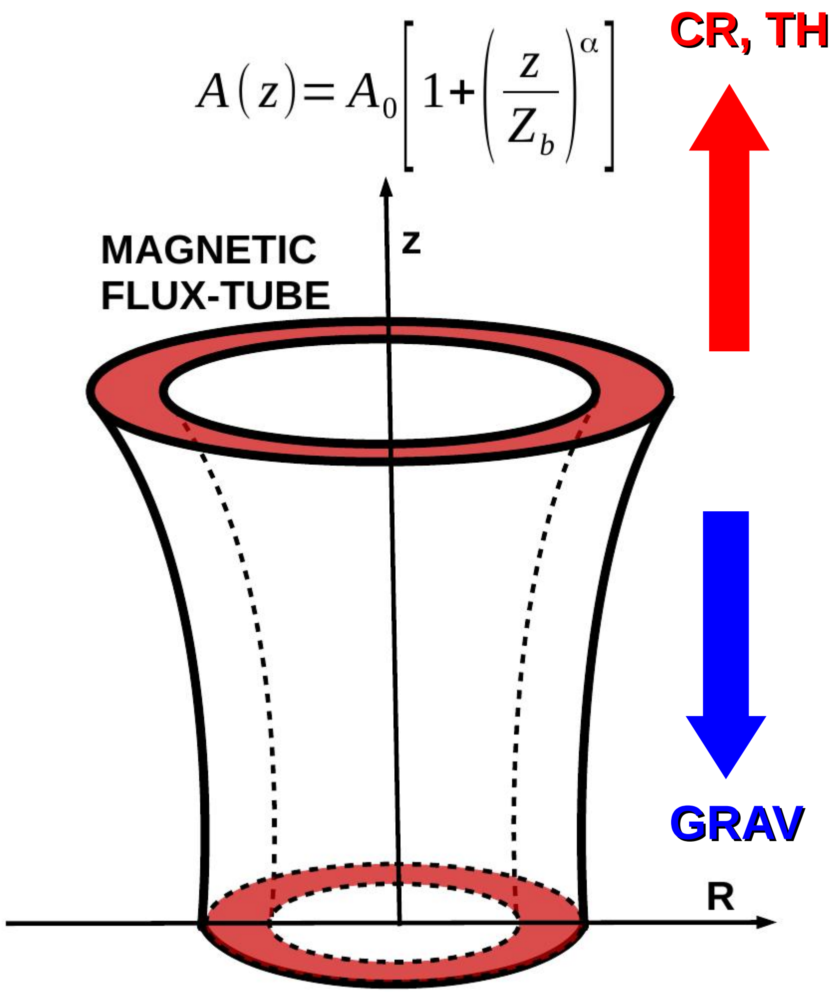
- **Thermal and radiation pressure not enough in the Milky Way**
- **Dynamical role of CRs** $E_{CR} \simeq E_{TH} \simeq E_{MAG}$
- **CR push against the gravitational force**

(Recchia et al. (2016))

- **CR diffusive and advective motion**
- **CR scattering and Effective coupling with ISM**
- **Role of self-generation of plasma waves and wave damping**
- **Effective propagation region becomes energy dependent**
- **Prominent effects on the CR spectrum**

WINDS HYDRODYNAMICS

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



- **One-dim model**: the flow and the CR transport occur along the magnetic field lines, perpendicular to the disk
- **Stationary flow**
- **Flux-tube geometry is preassigned**
- **CRs treated as a fluid**, pressure contribution
- **P_{CR} connected with the CR spectrum**
- **Damping of waves heats the gas**

WINDS HYDRODYNAMICS

z= distance from the galactic disk

MASS, MOMENTUM AND ENERGY CONSERVATION

$$\rho u A = const$$

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

HEATING DUE TO WAVE DAMPING

$$\frac{1}{u}\frac{du}{dz} = \frac{c_s^2 \frac{1}{A}\frac{dA}{dz} - g}{u^2 - c_s^2}$$

WIND EQUATION

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

GENERALIZED SOUND SPEED

HYDRODYNAMIC CR TRANSPORT

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

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

EFFECTIVE CR ADIABATIC INDEX

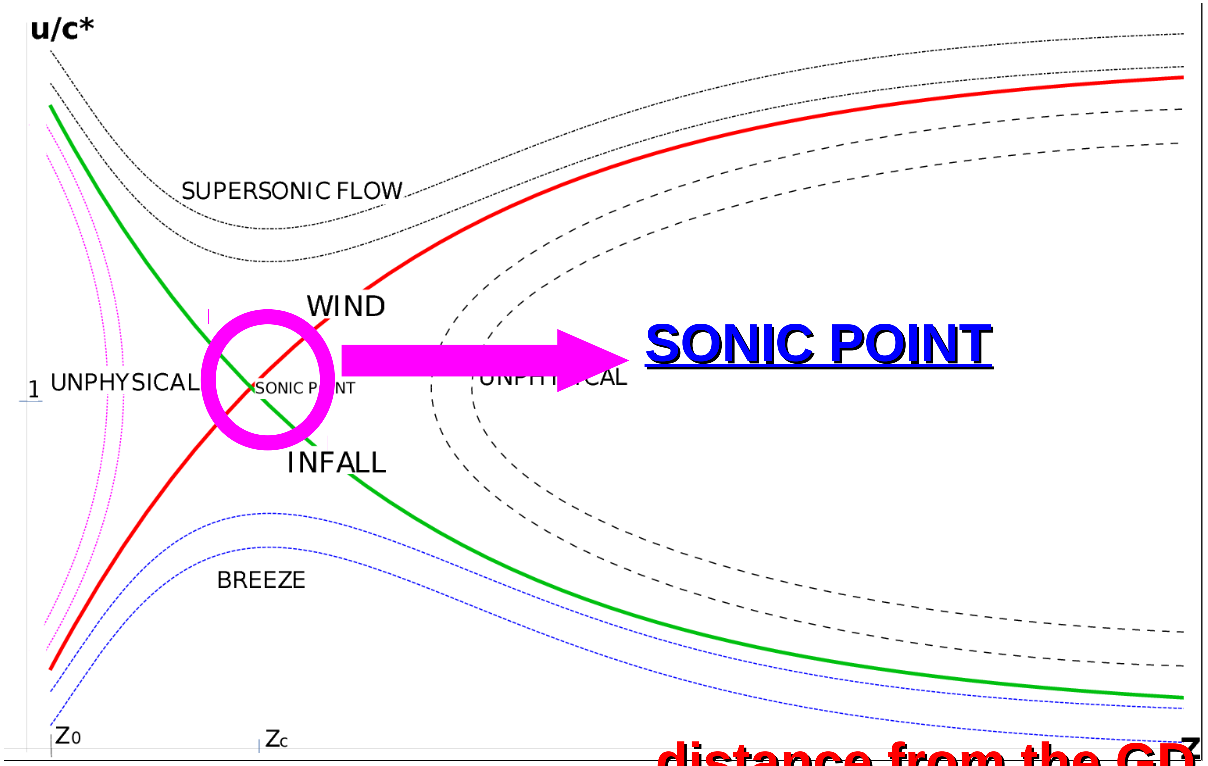
CR DIFFUSIVITY

WIND HYDRODYNAMICS

WIND EQUATION:

$$\frac{1}{u}\frac{du}{dz}=\frac{c_s^2\frac{1}{A}\frac{dA}{dz}-g}{u^2-c_s^2}$$

Flow speed



distance from the GD

WIND BASE:

Need to determine u0 that gives smooth transition to supersonic flow

CRITICAL POINTS OF THE WIND EQUATION:

NUM=0

DEN=0

RESULTS: HYDRODYNAMICS

THE WIND LAUNCHING DEPENDS ON:

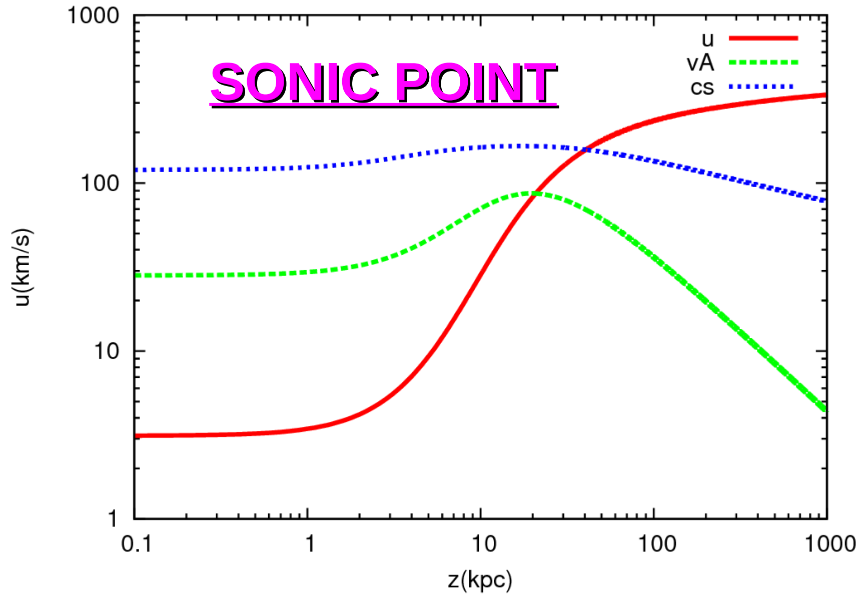
- input parameters at the wind base (n, T, B, Pc)
- flux-tube geometry
- Galactic gravitational potential (bulge, disk, Dark Matter halo)

CONSTRAINT FROM OBSERVATIONS, DEPENDENCE ON THE POSITION IN THE GALAXY

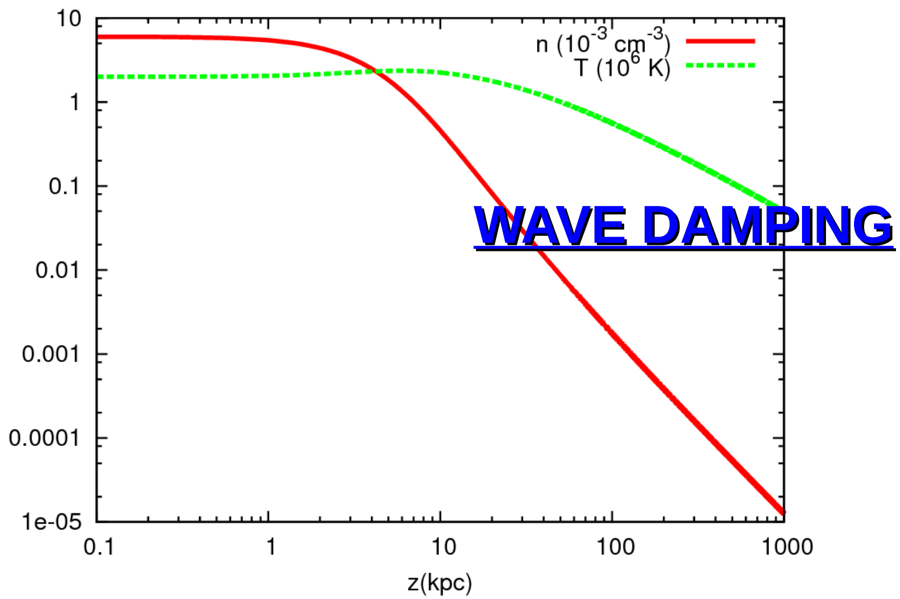
- **Wind solution exists for closed intervals of n, T, Pc, g**
- **Small n and g, large T and Pc:** non stationary outflows...
- **Large n and g, small T and Pc:** not enough energy for outflow...
- Stationary non transonic flows, non stationary flows...

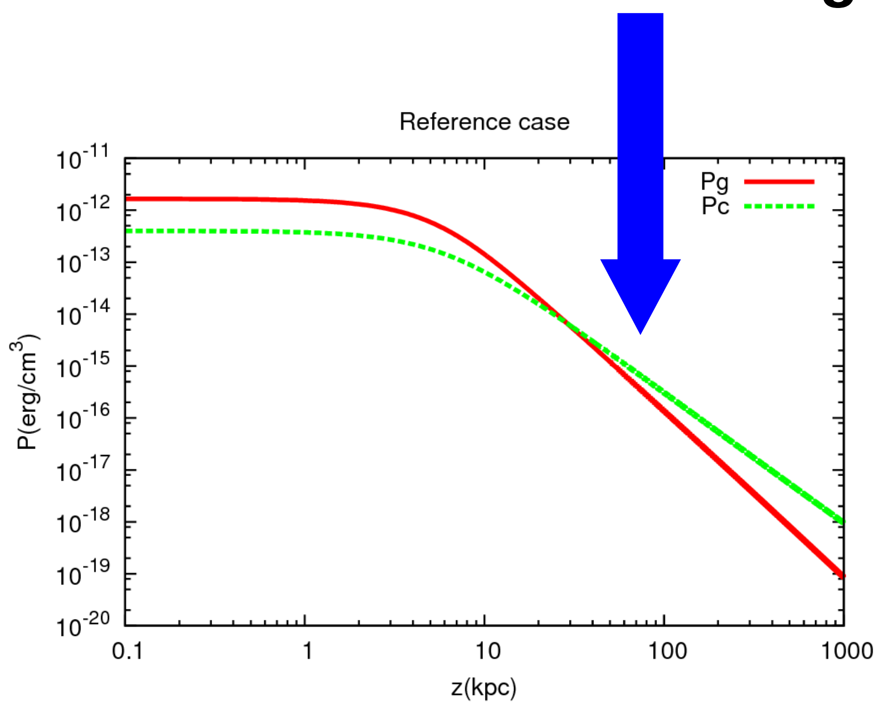
(Everett et al. (2008)) **(Recchia et al. (2016))**

HYDRODYNAMICS : TYPICAL CASE

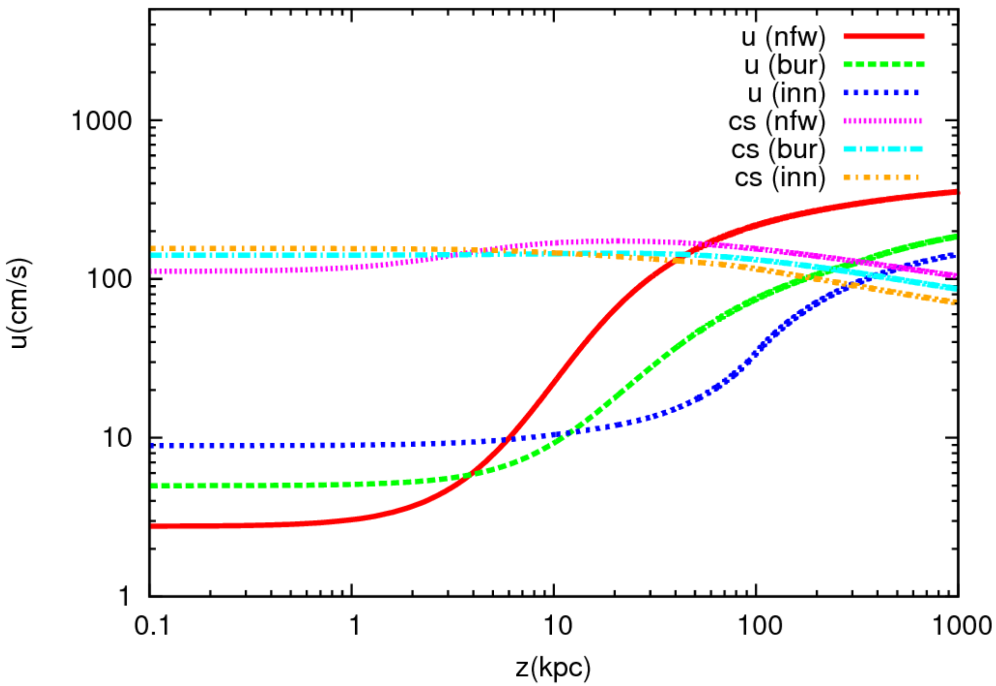


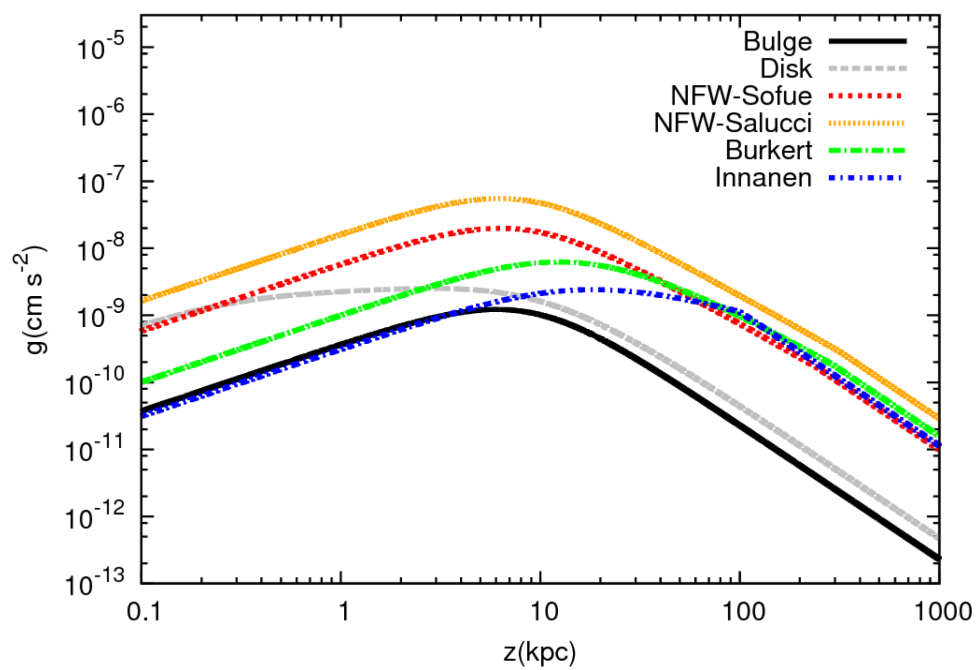
- $P_{CR} > P_{TH}$ @ ~10kpc
- CRs push all along the wind profile
- Different adiabatic index
- Crucial for wind launching





HYDRODYNAMICS: DM HALO





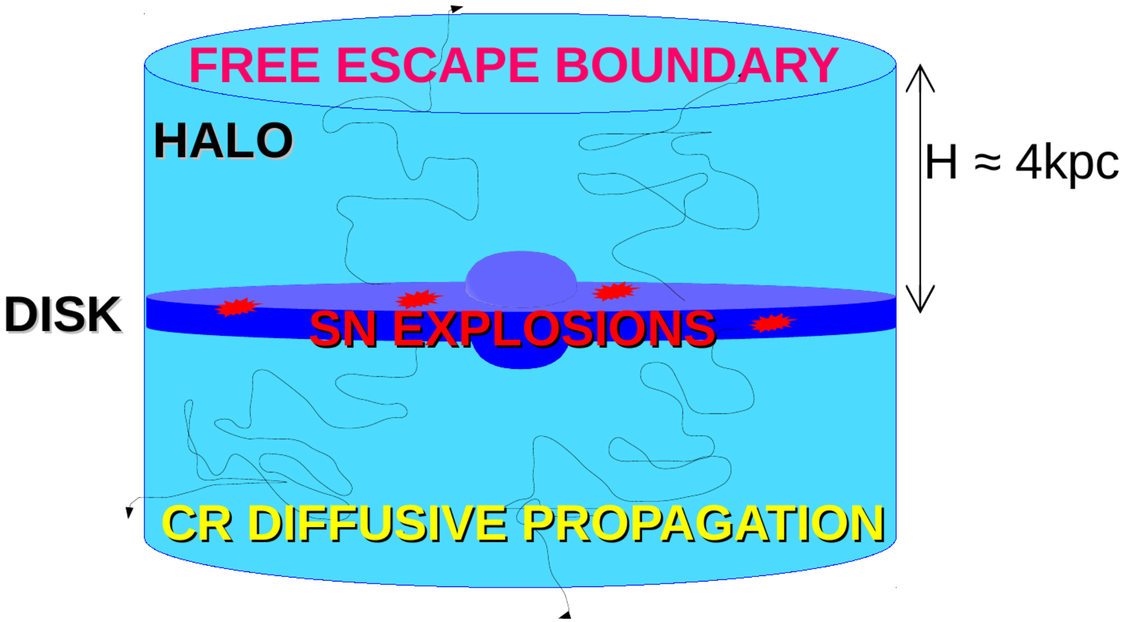
DM important also far from the disk

models of DM halo:

- **Navarro-Frenk-White (NFW)**
- **Burkert (BUR)**
- **Innanen(INN)**
- **Similar DM densities at the SUN**

both u_0 and u_f change

CR TRANSPORT: SIMPLE MODEL



$$Q_0(p) \sim p^{-\gamma} \qquad \gamma \sim 4.1$$

$$D(p) \sim p^{\delta} \qquad \delta \sim 0.6$$

CR TRANSPORT EQUATION

$$\boxed{\frac{-\partial}{\partial z}\left[D(p)\frac{\partial f}{\partial z}\right]} + \boxed{u\frac{\partial f}{\partial z}} - \boxed{\frac{du}{dz}\frac{p}{3}\frac{\partial f}{\partial p}} = \boxed{Q_0(p)\,\delta(z)}$$

INJECTION

DIFFUSION ADVECTION COMPRESSION

CR TRANSPORT: SIMPLE MODEL

ADVECTION DOMINATETED REGIME

- Low energies (below ~ 10 GeV)
- Spectral slope same as injection

$$f_0^{adv}(p) = \frac{Q_0}{2u} \sim p^{-\gamma}$$

DIFFUSION DOMINATETED REGIME

- High energies

$$f_0^{diff}(p) = \frac{Q_0}{2}\frac{H}{D} \sim p^{-\gamma-\delta}$$

- Spectral slope depends also on D(p)
- Dependence on the halo size?

WHAT SCATTERS CRs

- **Plasma (Alfvén) waves?**
- **Resonant scattering?**
- **Self-generation from CRs?**
- **Background turbulence?**
- **Damping mechanisms?**

- **Here we assume:**

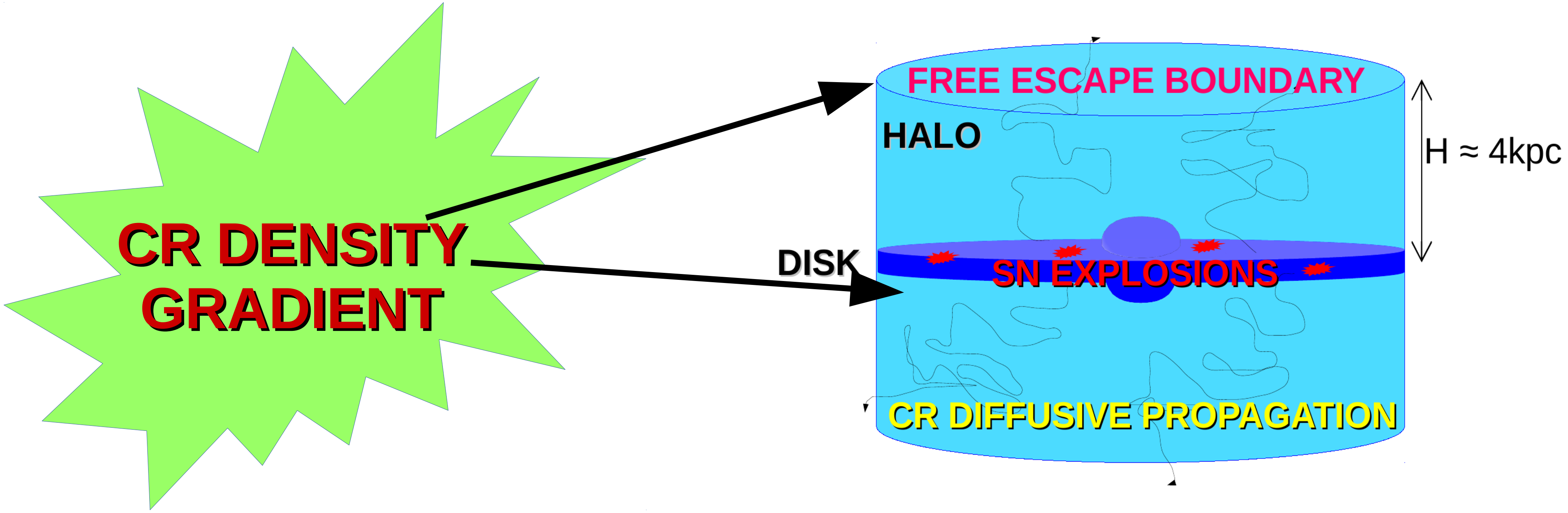
  Self-generation by streaming instability

  Damping by NLLD

  Background Kolmogorov turbulence

CR PROPAGATION : ISSUES

- **Physical processes which determine D, u and H?**
- **CR gradient**
- **CR induced diffusion**
- **Advection with self-generated waves**
- **CR-driven large scale flows (WINDS)**
- **Free escape boundary? Size of the propagation region**



SIZE OF THE DIFFUSIVE HALO

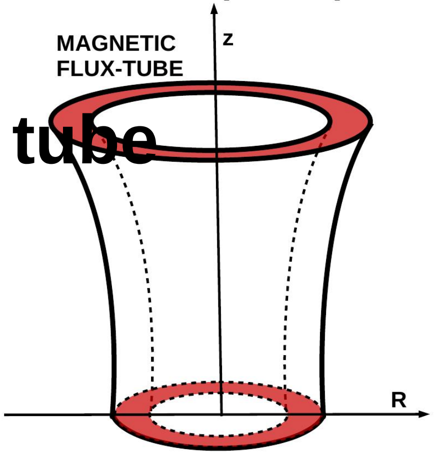
(Ptuskin et al. (1997)) (Recchia et al. (2016))

- u(z) grows with z
- At a given z*(p) advection overcome diffusion $u \sim u_0 z$

$$\frac{H^2(p)}{D} = \frac{H(p)}{u} \rightarrow H(p) \sim \sqrt{D}$$

- The size of the diffusive halo becomes energy dependent
- No need to impose H by hand output from the transport model
- Additional effects if z* is in the region of flux tube opening

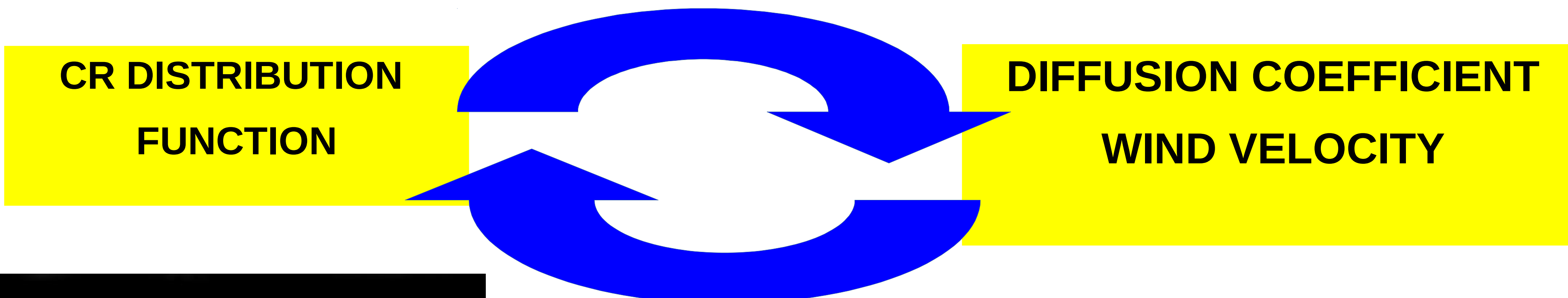
$$A(z) = A_0\left[1 + \left(\frac{z}{Z_b}\right)^{\alpha}\right]$$



CR TRANSPORT IN A CR-DRIVEN WIND

WIND HYDRODYNAMICS: determine the wind velocity, the gas density and pressure, the CR pressure and the magnetic field

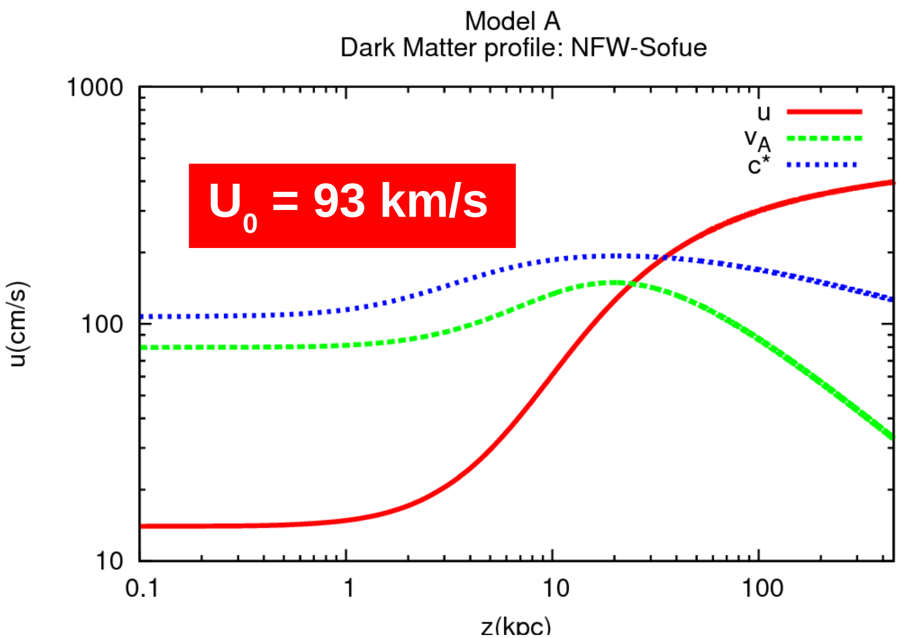
CR TRANSPORT: determine the CR distribution function and the CR-induced diffusion coefficient

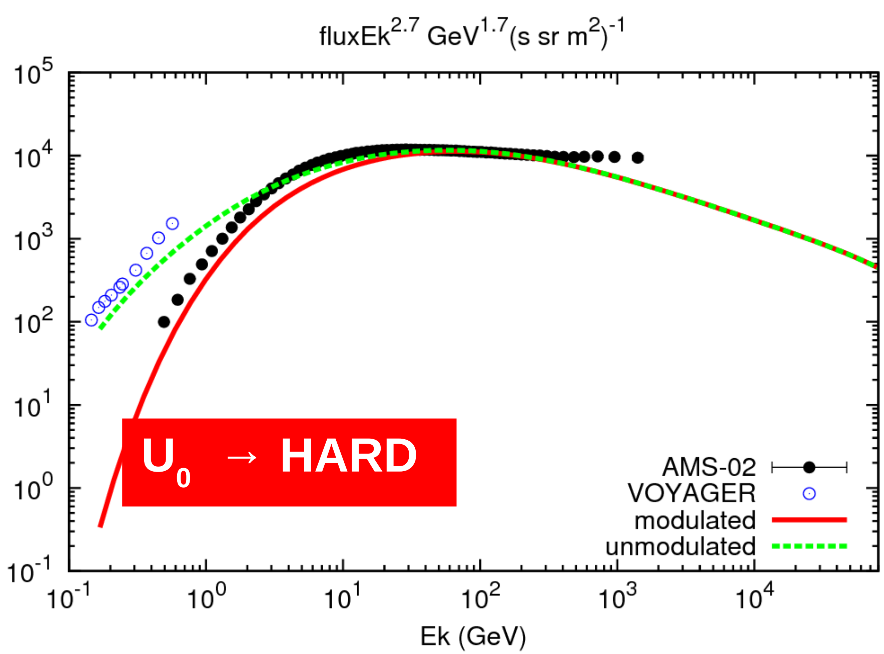


PROBLEM BADLY NON LINEAR

CR SPECTRUM AT EARTH

(Recchia et al. (2016))

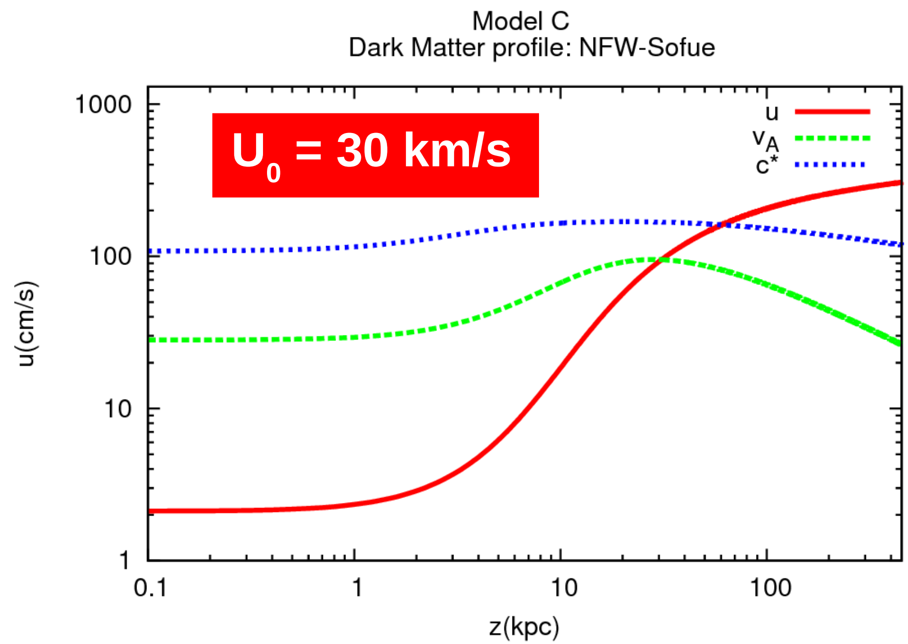


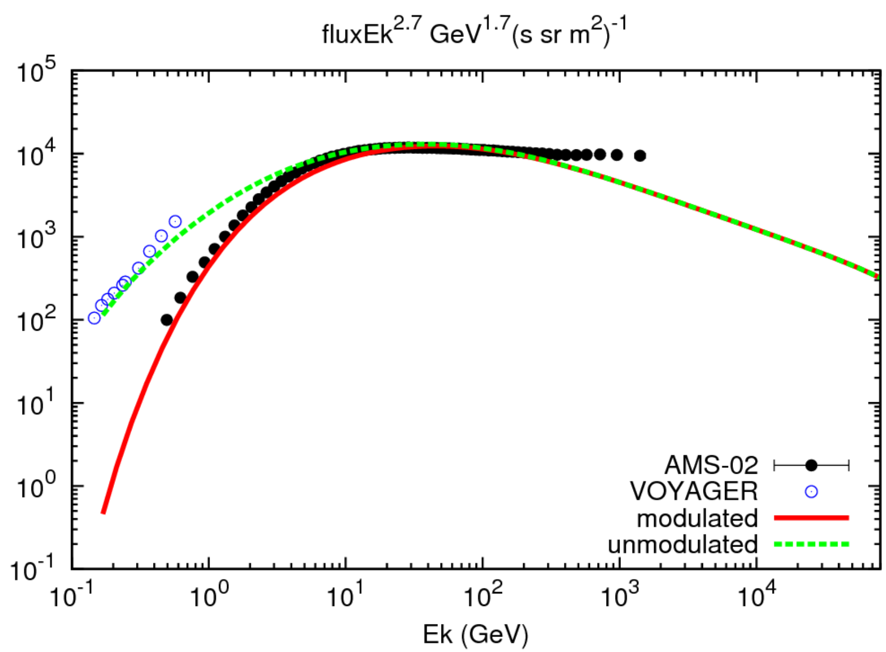


- **Wind lanched near the disk at Sun position**
- **launching param. within observations**
- **advection $v_A(z)+u(z)$**
- **Hard spectrum at low energies**

$$f_0^{adv}(p) = \frac{Q_0}{2u} \sim p^{-\gamma}$$

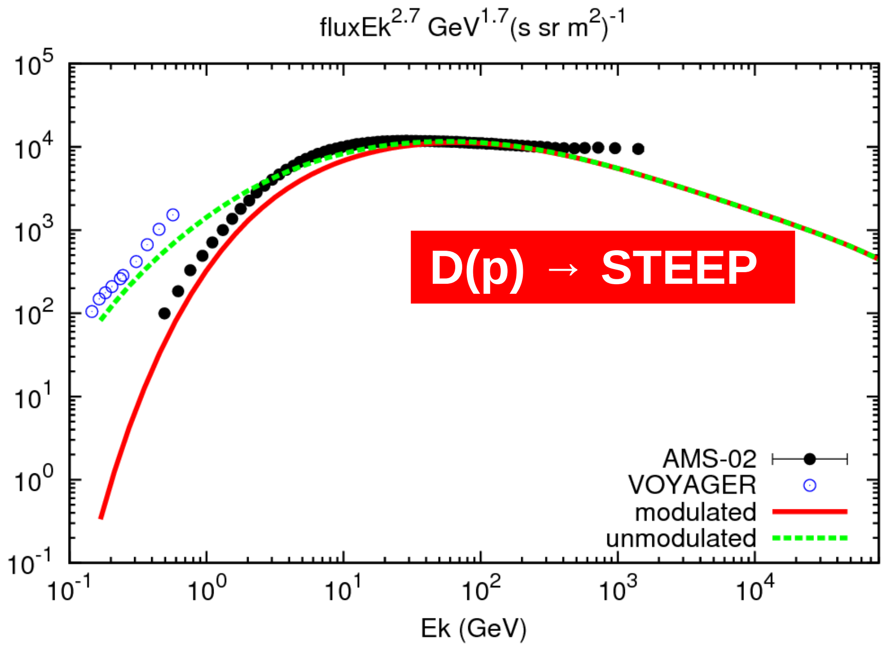
CR SPECTRUM AT EARTH

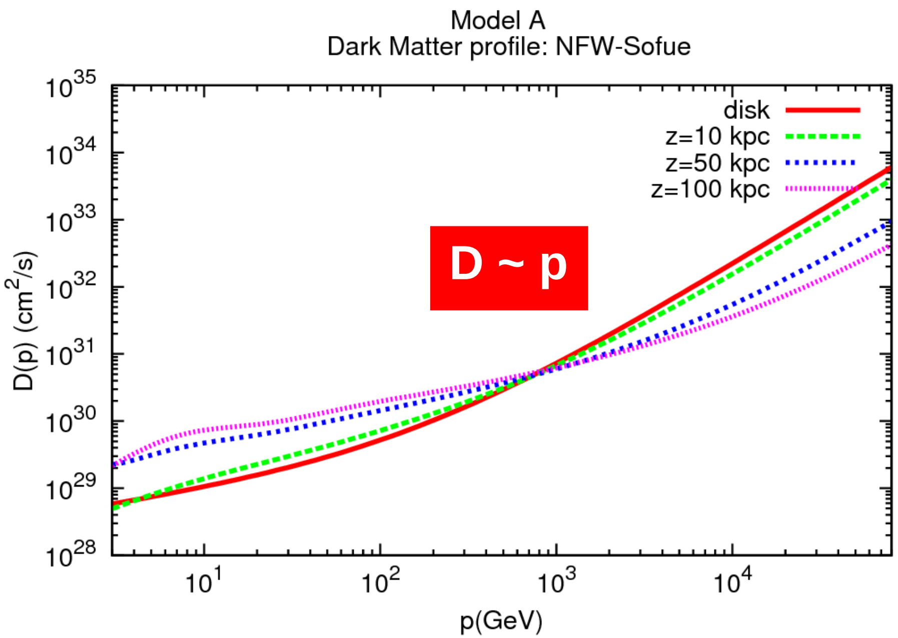




- wind launched at z_0 = 100 pc
- launching param. within observations
- U_0 = 30km/s VS 93km/s
- smaller advection, better agreement at low energy

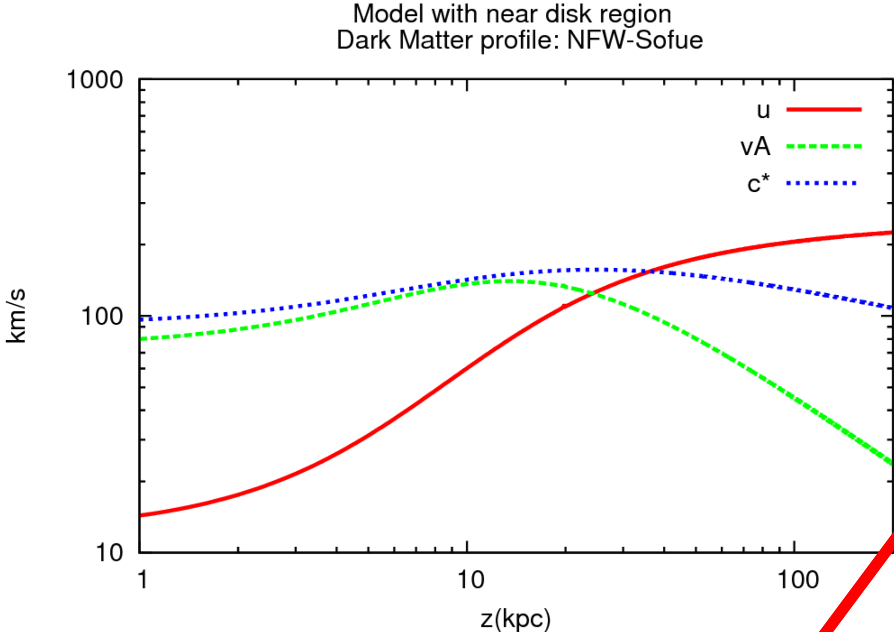
CR SPECTRUM AT EARTH

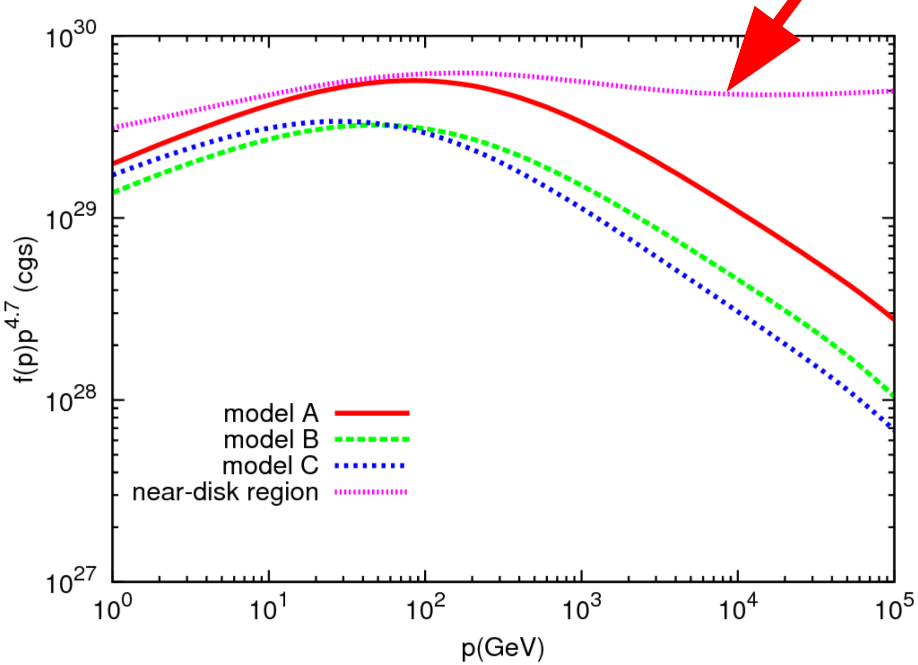




- **steep diffusion coefficient (self generation)**
- **wind expansion, H(p) in the expansion region**
- **very steep spectrum at high energy**
- **Need additional source of turbulence**

CR SPECTRUM AT EARTH





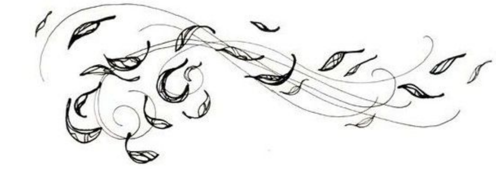
HARDENING

TRANSITION FROM SELF-GEN. D TO KOLMOGOROV ($D(p) \sim p^{1/3}$)

- **Role of pre-existing turbulence**
- **Spectral hardening at high energies**

(Aloisio et al. (2015))

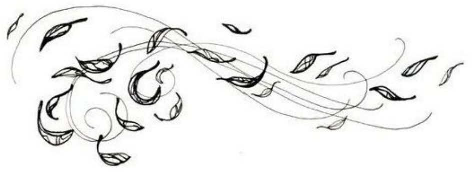
SUMMARY



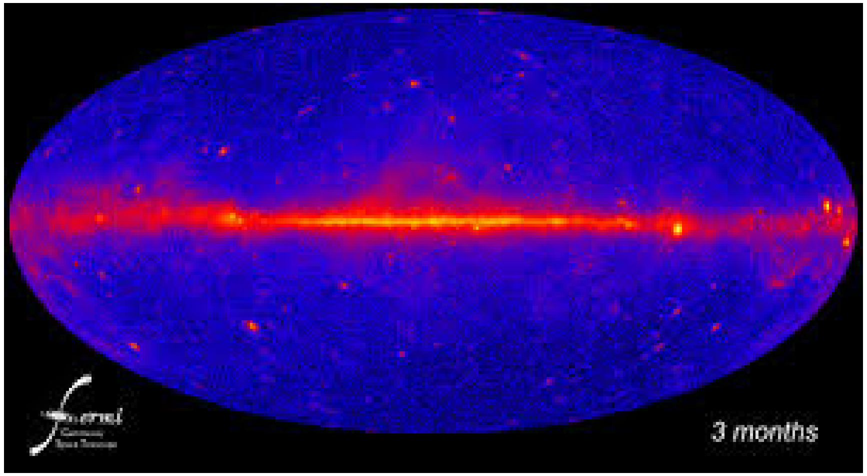
- Winds ubiquitous and important for galaxies
- Winds maybe also in the Milky Way (observation of the halo)
- CRs are likely to drive winds in the MW
- Strong dependence on the Galactic environment
- CR transport in CR driven winds
- Self-generation, advection, halo size
- Important implication for the CR spectrum

INTERESTING DEVELOPMENTS

- **Non stationary flows (fountains, winds, …)** (Dorfi et al. (2013)) (Ruszkowski et al.(2016))
- **Other stationary flows (Breezes)** (Taylor et al. (2017))
- **CR distribution in the Galaxy** (Recchia et al. (2016))
- **Transport of metals etc with the wind**
- **Implications on the CR grammage**
- **Reacceleration of CRs at the wind termination shock** (Zirakashvili et al. (2006))
- **Self consistent determination of the flux tube geometry** (Zirakashvili et al. (1996))
- **Application to other galaxies**



CR DISTRIBUTION: GAMMA-RAY DATA



- FermiLAT data
- Gamma-Rays → nCR (R)
- Catalogs → CR Sources(R)

R < 10 kpc

n_{CR} > than at R> 10 kpc

n_{CR} peak at 2-5 kpc

CR slope 2.5-2.6 at 3 kpc

R > 10 kpc

n_{CR} flatter than SN(R)

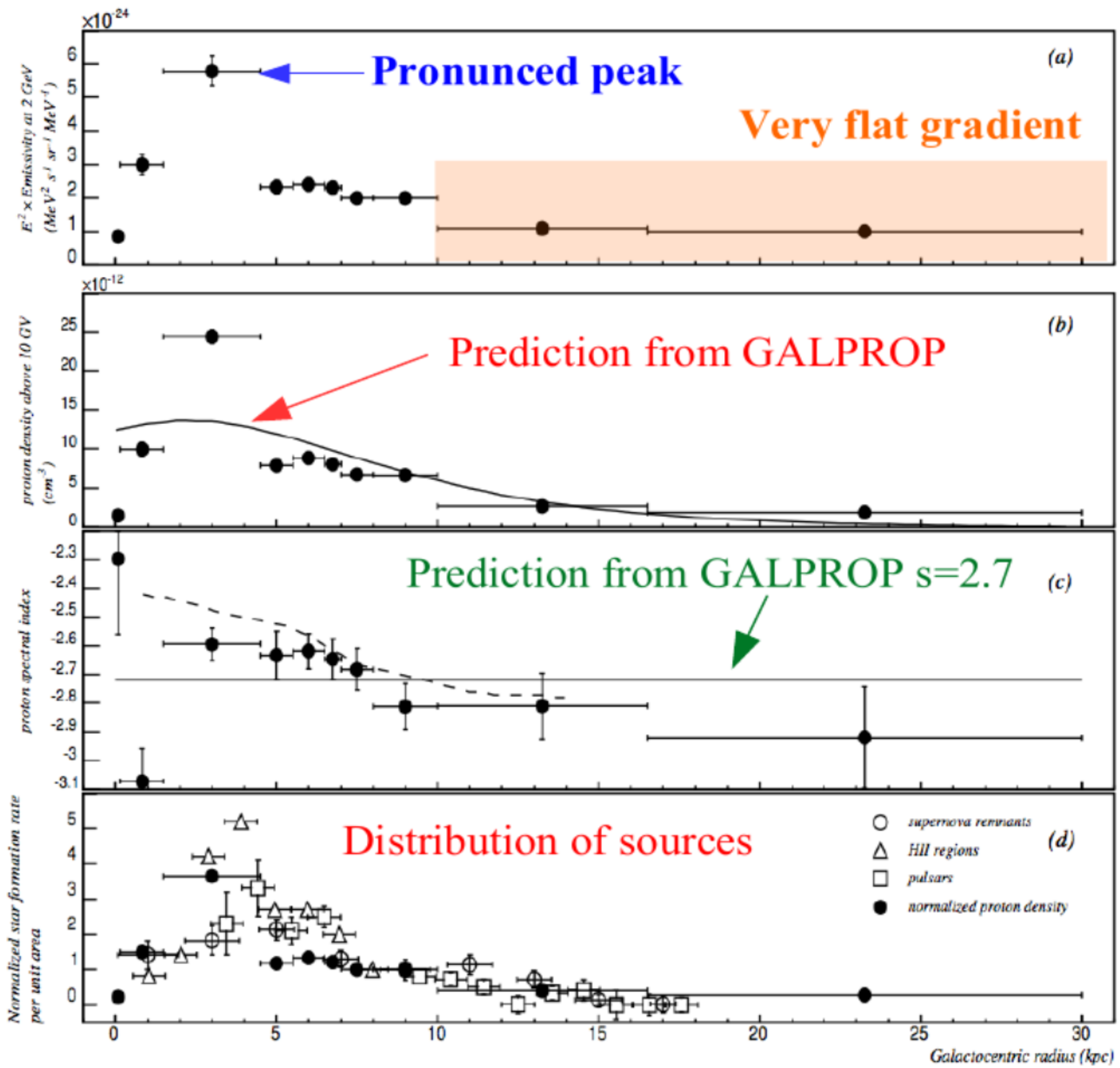
"radial gradient problem"

CR slope 2.8-2.9

A DIFFICULT INTERPRETATION

[Acero et al. ArXiv:1602.07246]

[Yang, Aharonian & Evoli, 2016]



- difficult to explain in a standard leaky-box model
- D constant in the Galaxy. Cannot explain $n_{CR}(R)$ and slope(R)
- Several extension of the leaky box have been proposed

PROPOSED SOLUTIONS

- Extended halo, H > 4 **(Dogiel, Uryson, 1988; Strong et al.,1988; Bloemen, 1993, Ackerman et al., 2011)**
- Flatter distribution of SNR in the outer Galaxy **(Ackerman et al., 2011)**
- Enhancement of CO/H_2 density ratio (X) in the outer Galaxy **(Strong et al., 2004)**
- Injection dependence on the ISM temperature **(Erlykin et al., 2015)**
- Advection effects due to the Galactic wind **(Bloemen, 1993; Breitschwerdt, Dogiel, Voelk, 2002)**

None of these ideas can simultaneously account for the both the CR density and spectral slope

RADIAL DEPENDENCE

- **Natural radial dependence in non-linear CR propagation, in particular with winds**
- Standard CR prop. Models → D constant in the Galaxy. Cannot explain $n_{CR}(R)$ and slope(R) **Evoli et al. (2012), Gaggero et al. (2015a,b)**

- **Galactic magnetic field and ISM density**

$$v_A(R) = \frac{B(R)}{4\pi\rho(R)}$$

$$D_{self-gen}(v_A, B, n_{CR})$$

$$u_{wind}$$

- **Injection of CRs, Galactic distribution of sources**

$$Q_0(p, R)$$

ASSUMPTIONS

- D is self generated
- V_A constant along z (perp. to the disk)
- Free escape boundary at z=H

- n(R)=const
- B(R) varies

$B_0(R)$	**const**	**R<5 kpc**
	1/R	**R>5 kpc**
[exp. cut-off		**R> 10 kpc]**

(GREEN 2015)

$$f_{SNR} \propto \left(\frac{R}{R_S}\right)^{\alpha} e^{-\beta \frac{R-R_s}{R_s}}$$

TRANSPORT EQUATION: SOLUTION WITHOUT WINDS

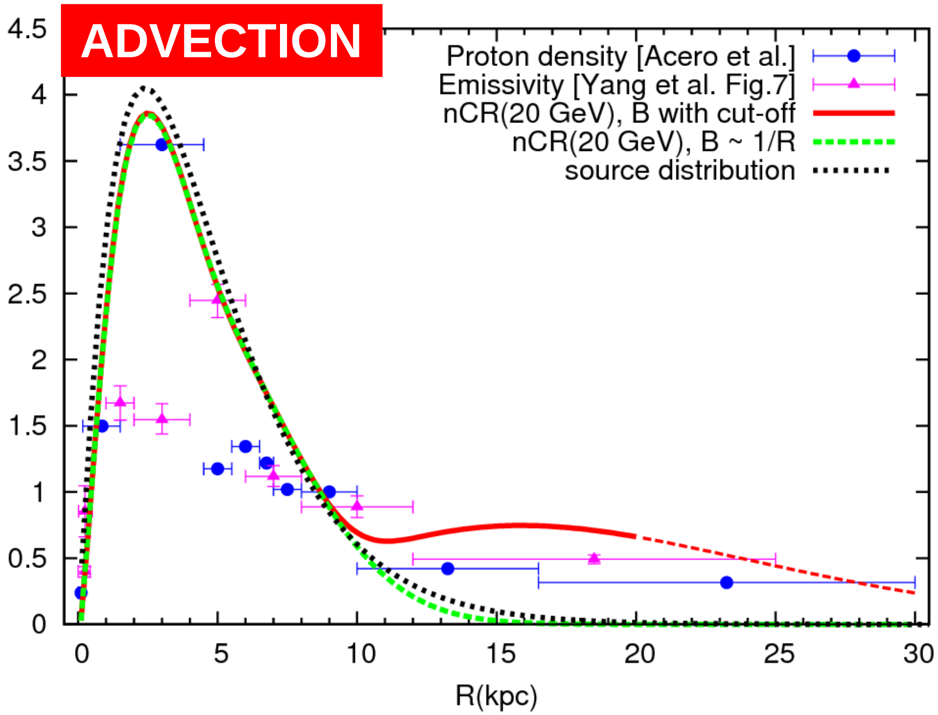
- **Injection Spectrum** $Q_0^{adv}(p) \sim p^{-\gamma}$ $\gamma \approx 4.3$

- **Diffusive regime** $f_0^{diff}(R) \sim \left(\frac{Q_0(R)}{B_0(R)}\right)^3$ $f_0^{diff}(p) \sim p^{7-3\gamma}$

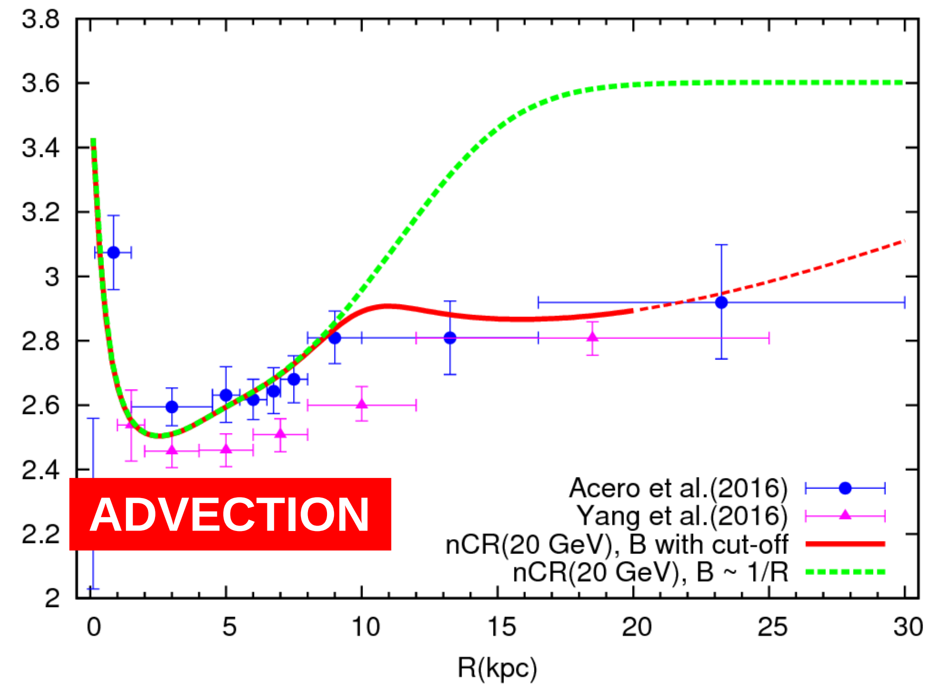
- **Advective regime** $f_0^{adv}(R) \sim \left(\frac{Q_0(R)}{B_0(R)}\right)$ $f_0^{adv}(p) \sim p^{-\gamma}$

CR RADIAL GRADIENT(NO WINDS)

CR density at 20 GeV



spectral slope at 20 GeV



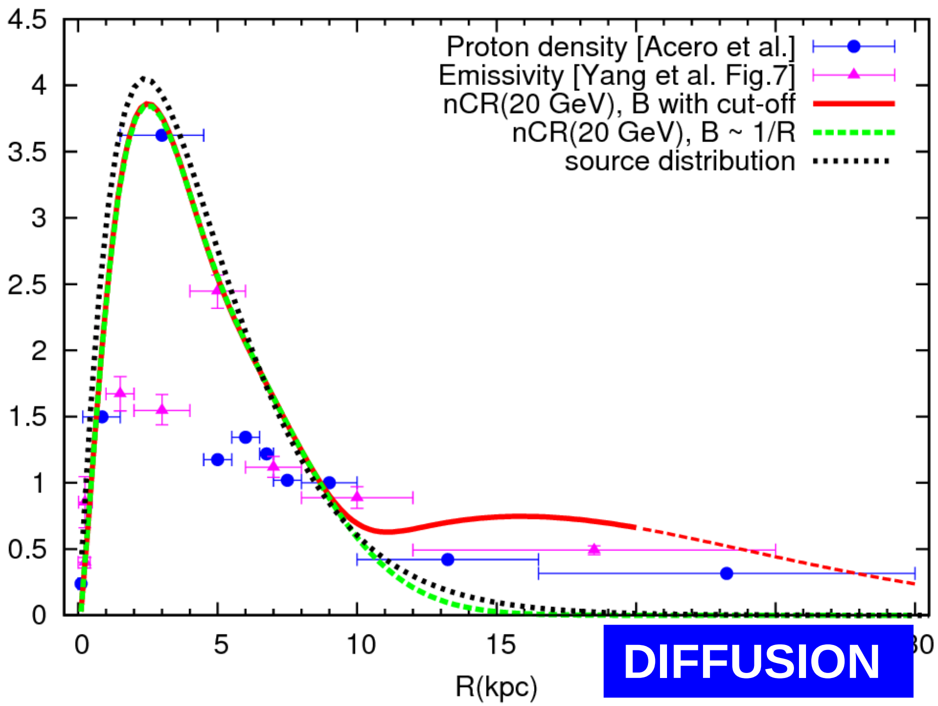
$$f_0^{adv} \sim \left(\frac{Q_0}{B_0}\right)$$

$$f_0^{adv}(p) \sim p^{-\gamma}$$

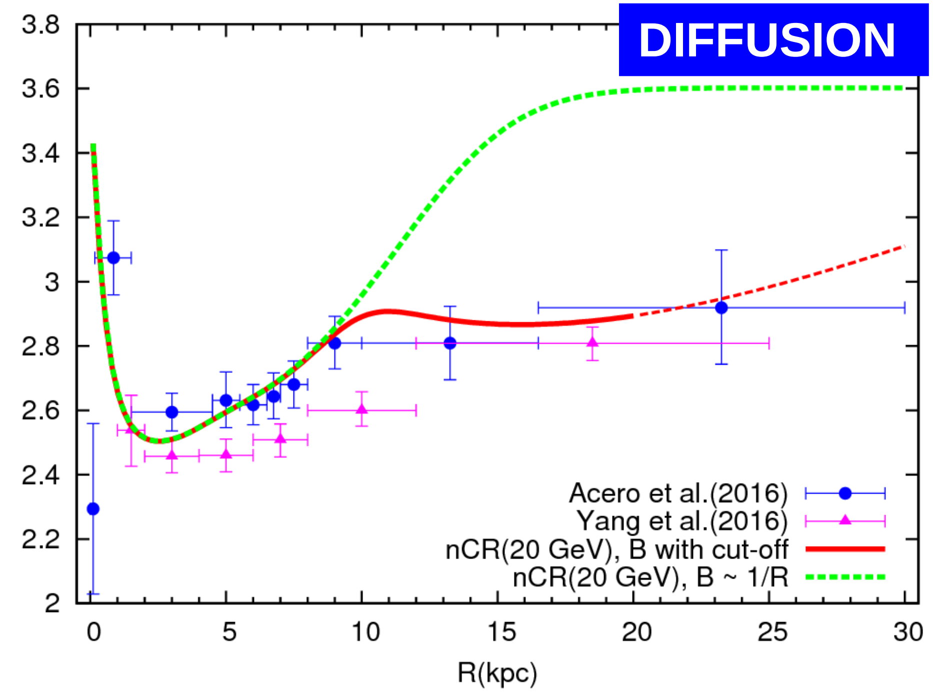
- **B~const**
- **peak Q0 ====> many waves =====> CRs well confined**
- **peak CR density**
- **advective regime =====> hard spectrum**

CR RADIAL GRADIENT(NO WINDS)

CR density at 20 GeV



spectral slope at 20 GeV



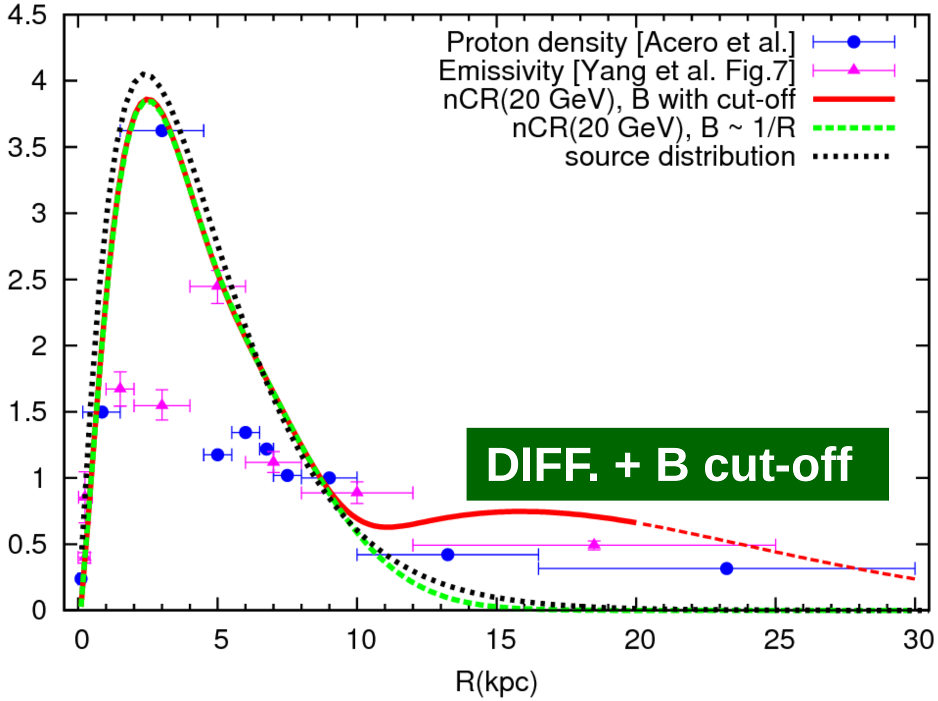
$$f_0^{diff} \sim \left(\frac{Q_0}{B_0} \right)^3$$

$$f_0^{diff}(p) \sim p^{7-3\gamma}$$

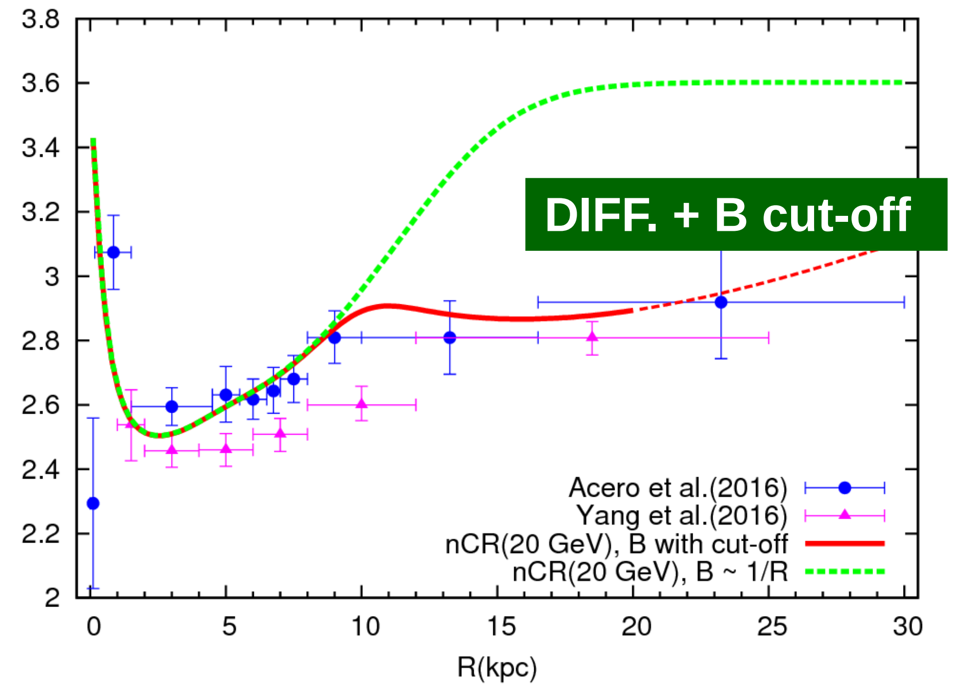
- **B~1/R**
- **small Q_0 ====> few waves =====> CRs poorly confined**
- **low CR density**
- **diffusive regime =====> steep spectrum**

CR RADIAL GRADIENT(NO WINDS)

CR density at 20 GeV



spectral slope at 20 GeV

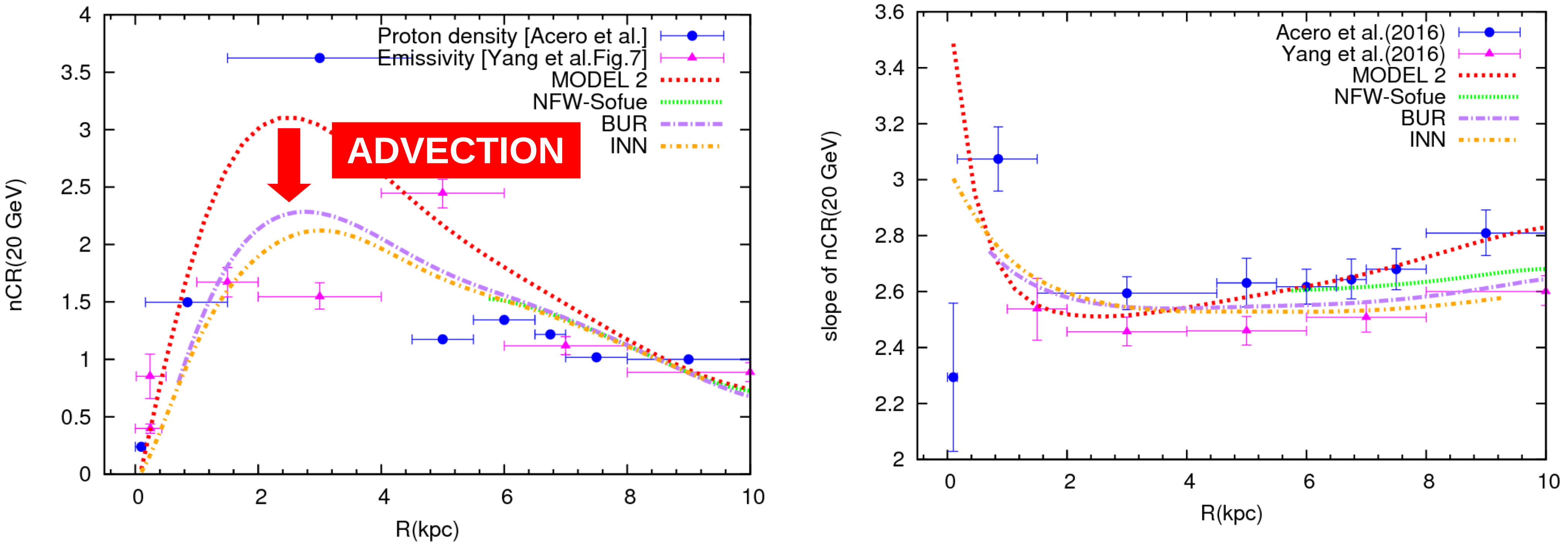


- B~1/R with exponential cut-off above R=10kpc
- small Q_0 + small B ====> D smaller despite few sources
- better confinement of CRs higher CR density
- B and Q_0 same R dependence ====> flatter CR density

Cut-off scale ~ 3kpc

Mixed diffusion/advection regime ====> harder CR spectrum

CR RADIAL GRADIENT(WINDS)



- **At the source peak: larger advection with wind → smaller CR density**
- **At the source peak: larger advection with wind VS larger D(less waves)**
- **At R > 10 kpc wind not launched (for the chosen input parameters)**
- **Results at R< 10 kpc depend on the Dark Matter halo potential**

WIND HYDRODYNAMICS

WIND EQUATION:

$$\frac{1}{u}\frac{du}{dz} = \frac{\frac{1}{A}\frac{dA}{dz} - g/c_s^2}{M^2 - 1}$$

DE LAVAL NOZZLE:

$$\frac{1}{u}\frac{du}{dz} = \frac{\frac{1}{A}\frac{dA}{dz}}{M^2 - 1}$$