NON LINEAR PROPAGATION OF GALACTIC COSMIC RAYS

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Sources of Galactic Cosmic Rays, Paris, 07-09 December 2016

WHY GOING NON LINEAR?

Too many features put by hands in phenomenological approaches (GALPROP, DRAGON, etc) - symptom of missing Physics

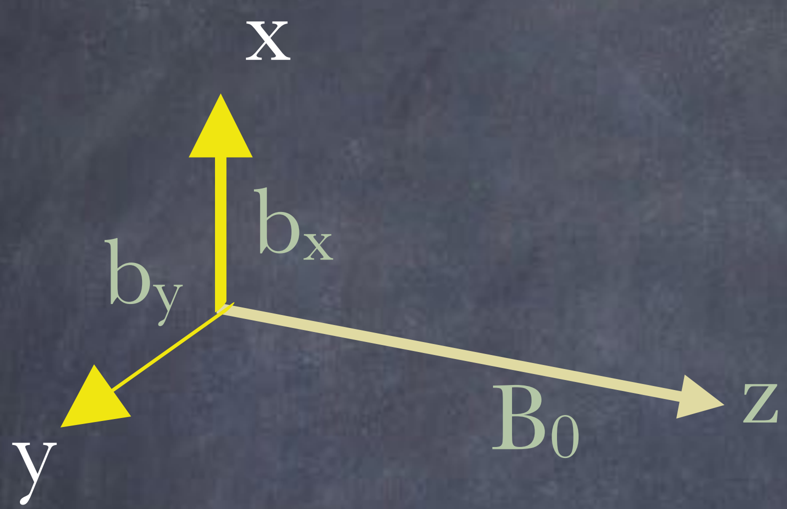
Diffusion of CRs is intrinsically non linear in nature due to momentum conservation

Many cases where we know such effects are in action (think of B-field amplification in SNRs)

1. NON LINEAR CR TRANSPORT ON GLOBAL GALACTIC SCALES
2. CR INDUCED GALACTIC WINDS WITH SELF-GENERATED WAVES
3. CR INDUCED INSTABILITIES AROUND GALACTIC SOURCES

Basics of CR Transport

A charged particle moving in a field B_0+b, with |b|<<B and b perpendicular to B_0 is:



THIS CHANGES $p_z = p\,\mu$

$$\frac{d\vec{p}}{dt} = q\frac{\vec{v}}{c} \times \left(\vec{B}_0 + \vec{b}\right)$$

THIS ONLY CHANGES p_x and p_y

$$\frac{d\mu}{dt} = \frac{qv}{pc}(1-\mu^2)^{1/2} b\, cos(\Omega t - kz + \psi), \qquad \Omega = \frac{qB_0}{mc\gamma}$$

Gyration Frequency

$$\langle \delta\mu \rangle_{\psi.t} = 0$$

Resonance

$$\langle \delta\mu\delta\mu \rangle_{\psi.t} = \frac{q^2 v^2 (1-\mu^2) b^2}{c^2 p^2 \mu} \delta(k - \Omega/v\mu)\delta t \propto \delta t$$

Diffusion

$$D_{\mu\mu} = \left\langle \frac{\Delta\theta\Delta\theta}{\Delta t} \right\rangle = \frac{\pi}{4}\,\Omega\, k_{res} F(k_{res})$$

FRACTIONAL POWER $(\delta B/B_0)^2$ $= G(k_{res})$

$$\tau \approx \frac{1}{\Omega\, G(k_{res})} \quad \Rightarrow \quad \left\langle \frac{\Delta z \Delta z}{\Delta t} \right\rangle \approx v^2\, \tau = \frac{v^2}{\Omega\, G(k_{res})}$$

SPATIAL DIFFUSION COEFF.

The net effect of spatial diffusion is to reduce the momentum of the particles in the z direction… forcing them, eventually, to move at the same speed as the waves v_w

$$n_{CR} m v_{dr} \to n_{CR} m v_w \to \frac{dp_{CR}}{dt} = \frac{n_{CR}(v_{dr} - v_w)}{\tau_{90}}$$

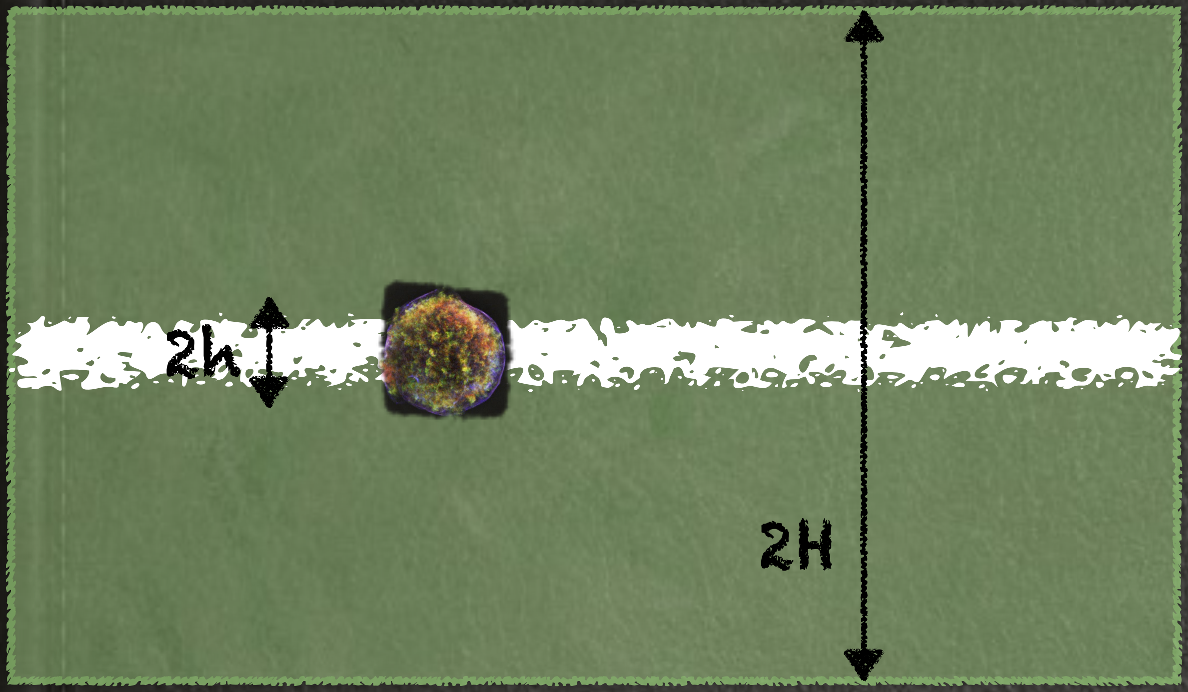
$$\frac{dp_w}{dt} = \Gamma_{CR} \frac{b^2}{8\pi v_w}$$

And requiring some balance between the two:

$$\Gamma_{CR} \approx \frac{n_{CR}}{n_i} \frac{v_{dr} - v_w}{v_w} \Omega_{cyc}$$

If CR stream faster than the waves, the net effect of diffusion is to make waves grow and make CR diffusive motion slow down… this process is known as self-generation of waves

Basics of Galactic CR Transport



$$-\frac{\partial}{\partial z}\left[D\frac{\partial f}{\partial z}\right] = Q_0(p)\delta(z)$$

DIFFUSION SNR as SOURCES

$p^{-\gamma}$ p^{δ}

$$f_0(p) = \frac{N_{inj}(p)R_{SN}}{\pi R_{disc}^2\; 2H}\frac{H^2}{D(p)} \sim p^{-\gamma-\delta}$$

$$D\frac{\partial f}{\partial z} = Constant \rightarrow f(z) = f_0\left(1-\frac{z}{H}\right)$$

$$\frac{\partial f}{\partial z} = -\frac{f_0}{H}$$

PARTICLES ESCAPE AT |Z|=H -> FREE ESCAPE BOUNDARY !

CR-INDUCED INSTABILITIES

INSTABILITIES ARE PRODUCED AS A RESULT OF A CR NET CURRENT THAT THE BACKGROUND PLASMA TRIES TO COMPENSATE FOR

THE INSTABILITY GROWS AT A RATE THAT DEPENDS UPON THE WAVENUMBER K OF THE MODES AND THE CONDITIONS IN THE ENVIRONMENT

IF THE CR CURRENT IS J_{CR} THEN GROWTH IS FASTER AT

$$k_{max} B_0 = \frac{4\pi}{c} J_{CR} \rightarrow k_{max} r_L = \frac{1}{U_B} \left(\frac{v_d}{c}\right) n_{CR}(>E)E$$

$k_{max} r_L >> 1$ Non Resonant (Bell) mode [High CR E-density]

$k_{max} r_L \approx 1$ Resonant mode [Low CR E-density]

Growth rate can be written as: $\Gamma_{max} \approx k_{max} v_A$

GROWTH OF THE RESONANT MODE

This regime is realised when the CR current is small

$$\frac{1}{U_B}\left(\frac{v_d}{c}\right) n_{CR}(>E)E \leq 1$$

and the growth rate can be rewritten as:

$$\gamma_{max}(k) \approx \frac{n_{CR}(>E)}{n_g}\frac{v_d}{v_A}\Omega_{cyc} \qquad k = 1/r_L(E)$$

or, using the transport equation

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

In numbers $T_{CR}(E) \sim 10^3$ yr E_{GeV}^{-1} namely the instability grows on very short time scales and is bound to affect CR transport

PB, Amato & Serpico 2012PhRvL, 109, 1101
Aloisio & PB, 2013JCAP, 07, 001
Aloisio, PB & Serpico, 2015A&A, 583, 95
Recchia, PB & Morlino, 2016MNRAS, 462, 88

1) CR INDUCED INSTABILITIES ON GALACTIC SCALES

Transport equation for all nuclei

$$-\frac{\partial}{\partial z}\left[D_\alpha(E)\frac{\partial f_\alpha}{\partial z}\right] + v_A \frac{\partial f_\alpha}{\partial z} + \frac{f_\alpha}{\tau_{sp,\alpha}} - \frac{dv_A}{dz}\frac{p}{3}\frac{\partial f_\alpha}{\partial p} + \frac{1}{p^2}\frac{\partial}{\partial p}\left[p^2\left(\frac{dp}{dt}f_\alpha\right)_{ion}\right]$$

$$q_{inj}(p) + \sum_{\alpha'>\alpha}\frac{f_{\alpha'}}{\tau_{sp,\alpha'\to\alpha}}$$

Power law in p

α DENOTES THE TYPE OF NUCLEUS (BOTH PRIMARIES AND SECONDARIES ARE INCLUDED)

$$D_\alpha(p) \approx \frac{1}{3} r_{L,\alpha} v_\alpha(p) \frac{1}{\mathcal{F}(k_{res,\alpha})} \qquad k_{res,\alpha} = \frac{1}{r_{L,\alpha}} = \frac{Z_\alpha e B_0}{pc}$$

All nuclei contribute to the development of the streaming instability, each with its own gradient and at the relevant resonant wavenumber

Evolution of the waves

$$\frac{\partial}{\partial k}\left[D_{kk}\frac{\partial W}{\partial k}\right] + \Gamma_{\rm CR} W = q_W(k)$$

Diffusion in k-space models damping

Waves' Growth as due to CR streaming

Wave source term $\delta(k-k_0)$

$$\Gamma_{CR}(k) = \frac{16\pi^2}{3}\frac{v_A}{B_0^2\mathcal{F}(k)}\sum_\alpha\left[p^4 v_\alpha(p)\frac{\partial f_\alpha}{\partial z}\right]_{p=p_{res,\alpha}(k)}$$

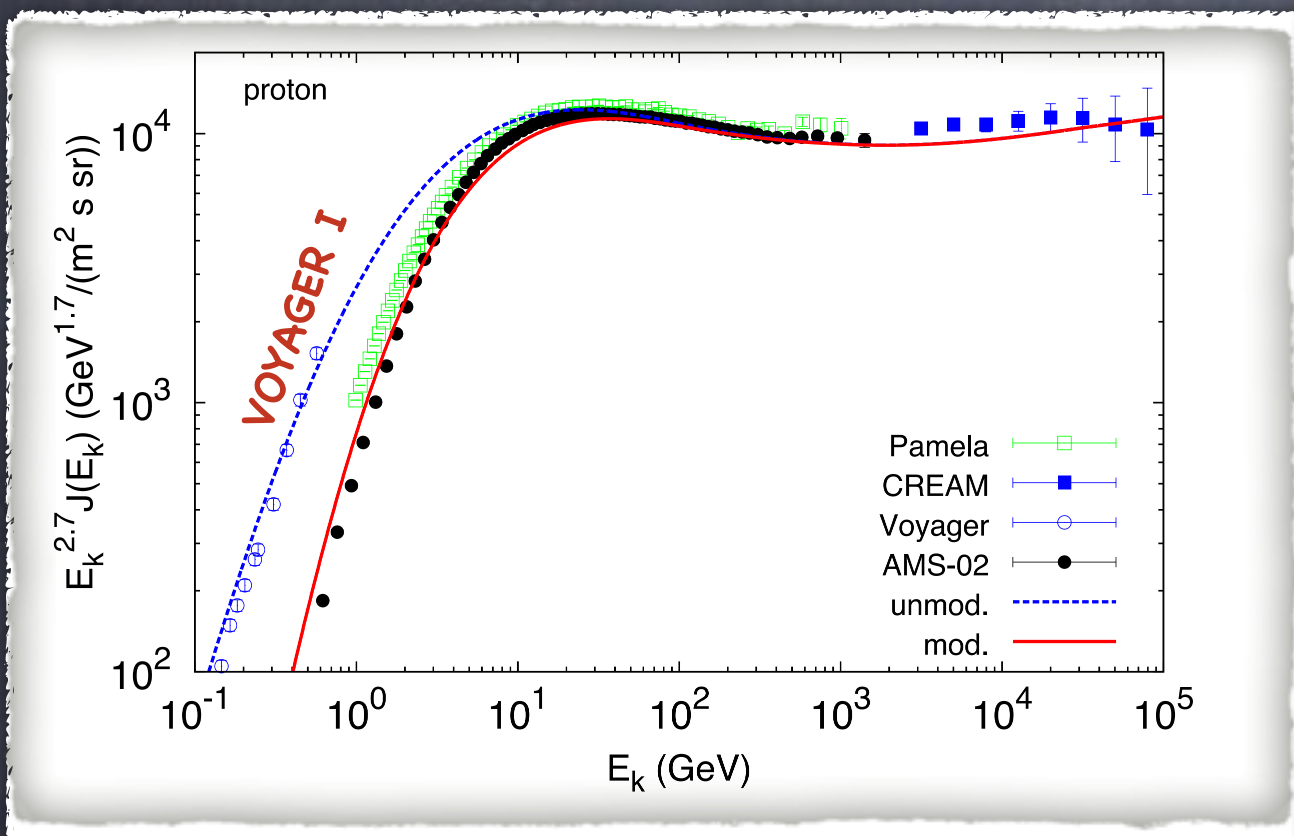
SUM OVER ALL NUCLEI OF THE RIGHT MOMENTUM TO GENERATE A WAVE WITH GIVEN k

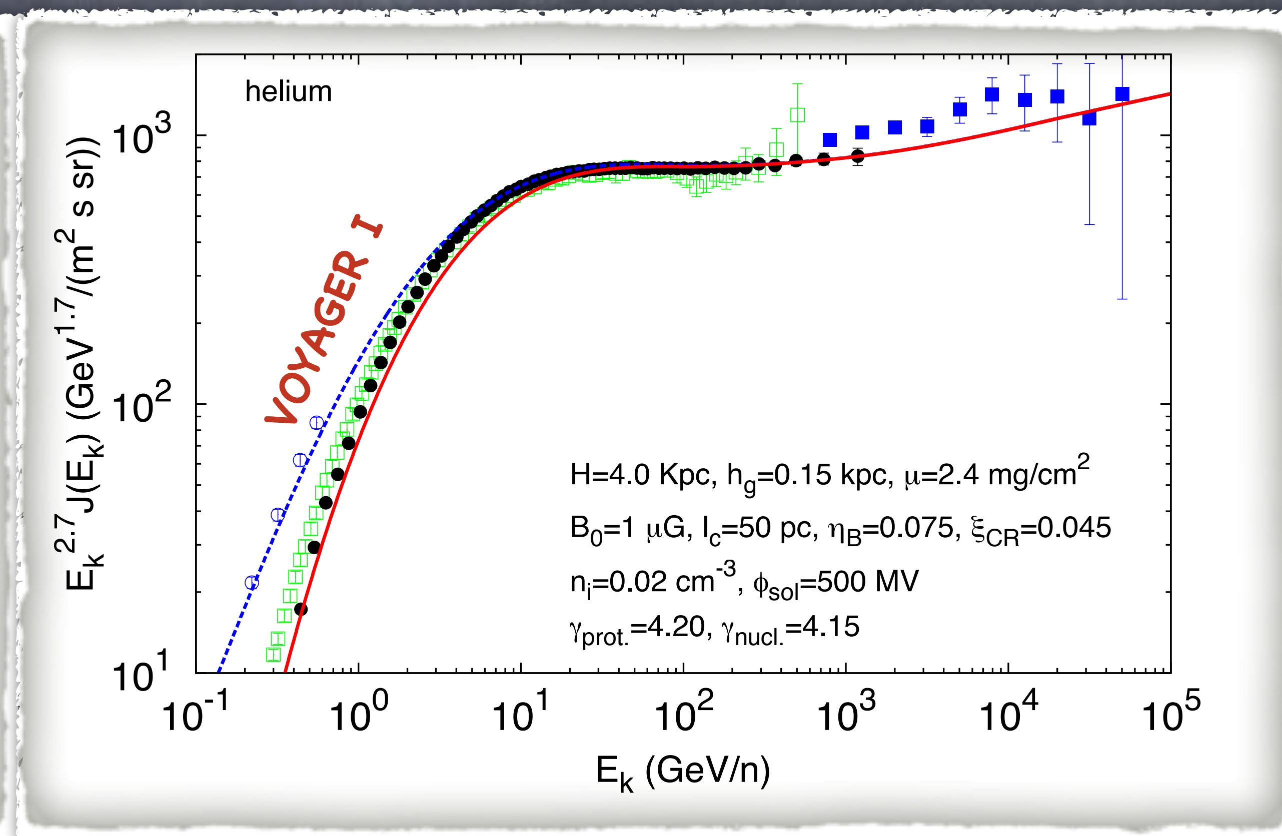
$$D_{kk} = C_K v_A k^{7/2}\left(\frac{\mathcal{F}}{k}\right)^{1/2} \qquad C_K \sim 5\times 10^{-2}$$

IN THE ABSENCE OF THE INSTABILITY THE EQUATION ABOVE RETURNS A KOLMOGOROV SPECTRUM. WITH THE GROWTH TERMS RETURNS A BROKEN POWER SPECTRUM OF TURBULENCE

Spectral Breaks: self-generation vs previous turbulence

Aloisio, PB & Serpico 2015

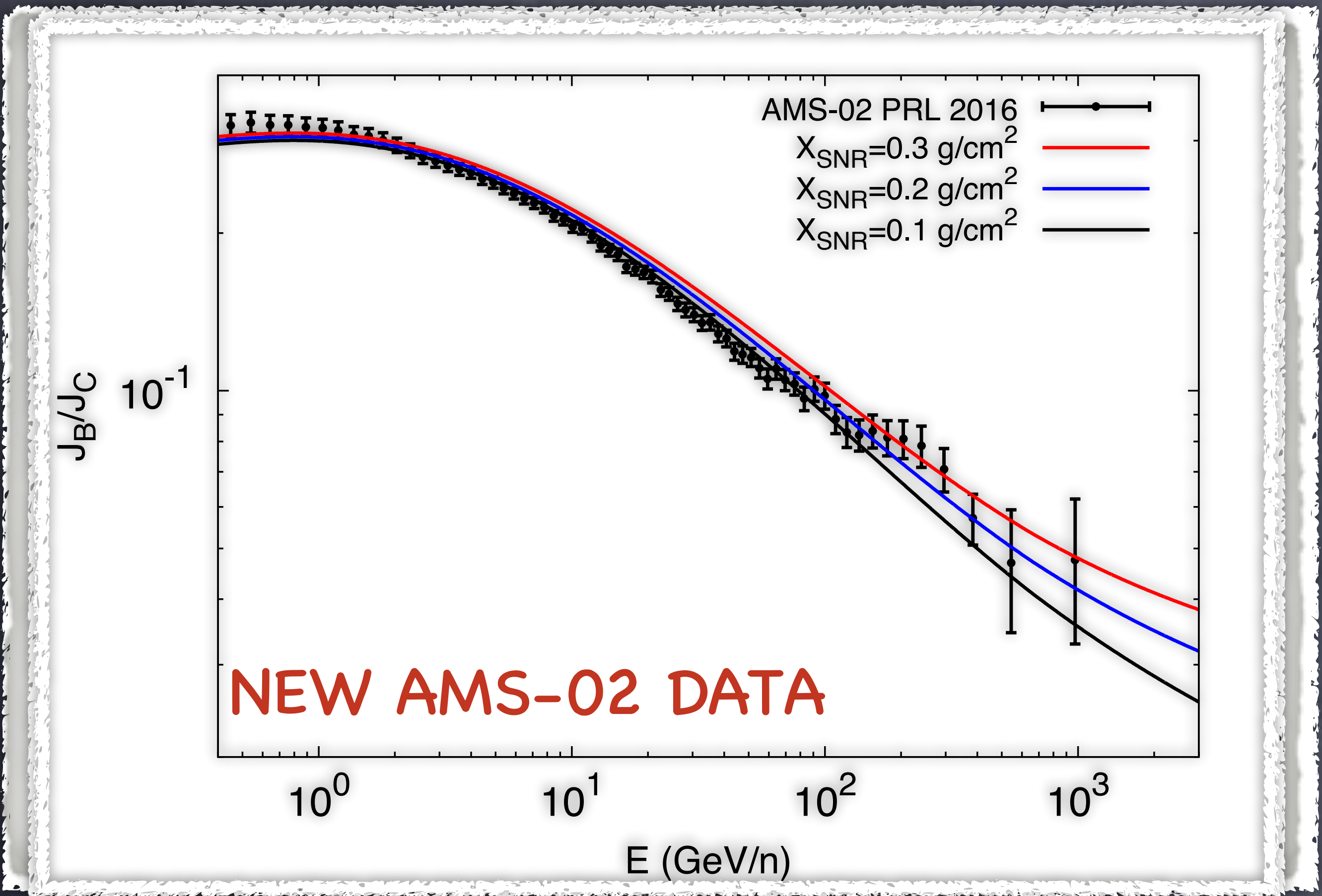


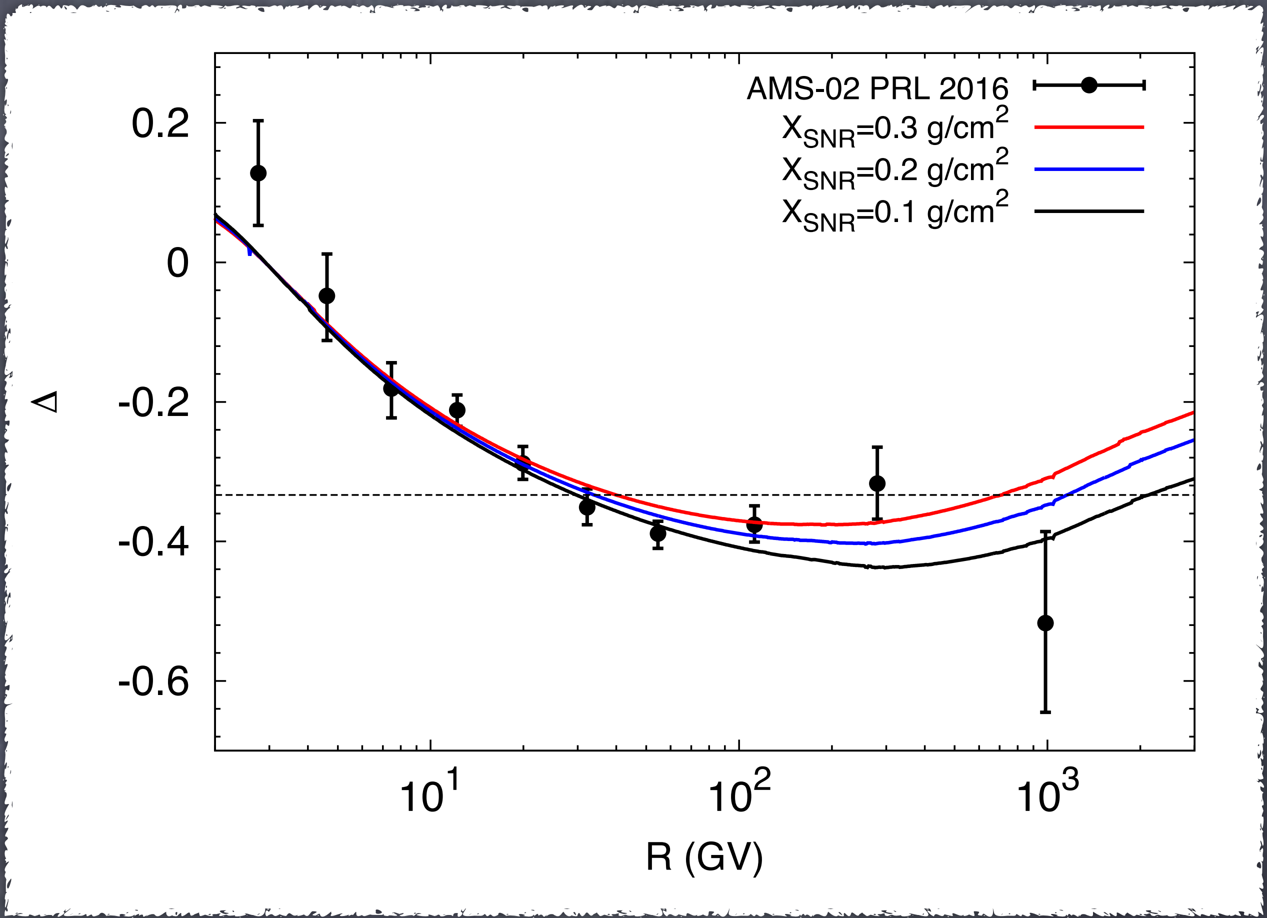


PAMELA and AMS-02 data — combination of self-generated and pre-existing waves

Voyager data are automatically fitted with no additional breaks… advection with self-generated waves at E<10 GeV?

THE AMS-02 B/C RATIO





THE AMS-02 B/C RATIO CAN BE EXPLAINED AS A CONSEQUENCE OF THE WAVE SELF-GENERATION PLUS THE UNAVOIDABLE GRAMMAGE INSIDE SOURCES

$$X_{\rm SNR} \approx 1.4 r_s m_p n_{\rm ISM} c T_{\rm SNR} \approx 0.17\,{\rm g\,cm^{-2}} \frac{n_{\rm ISM}}{\rm cm^{-3}} \frac{T_{\rm SNR}}{2\times 10^4 {\rm yr}}$$

The CR Radial Gradient

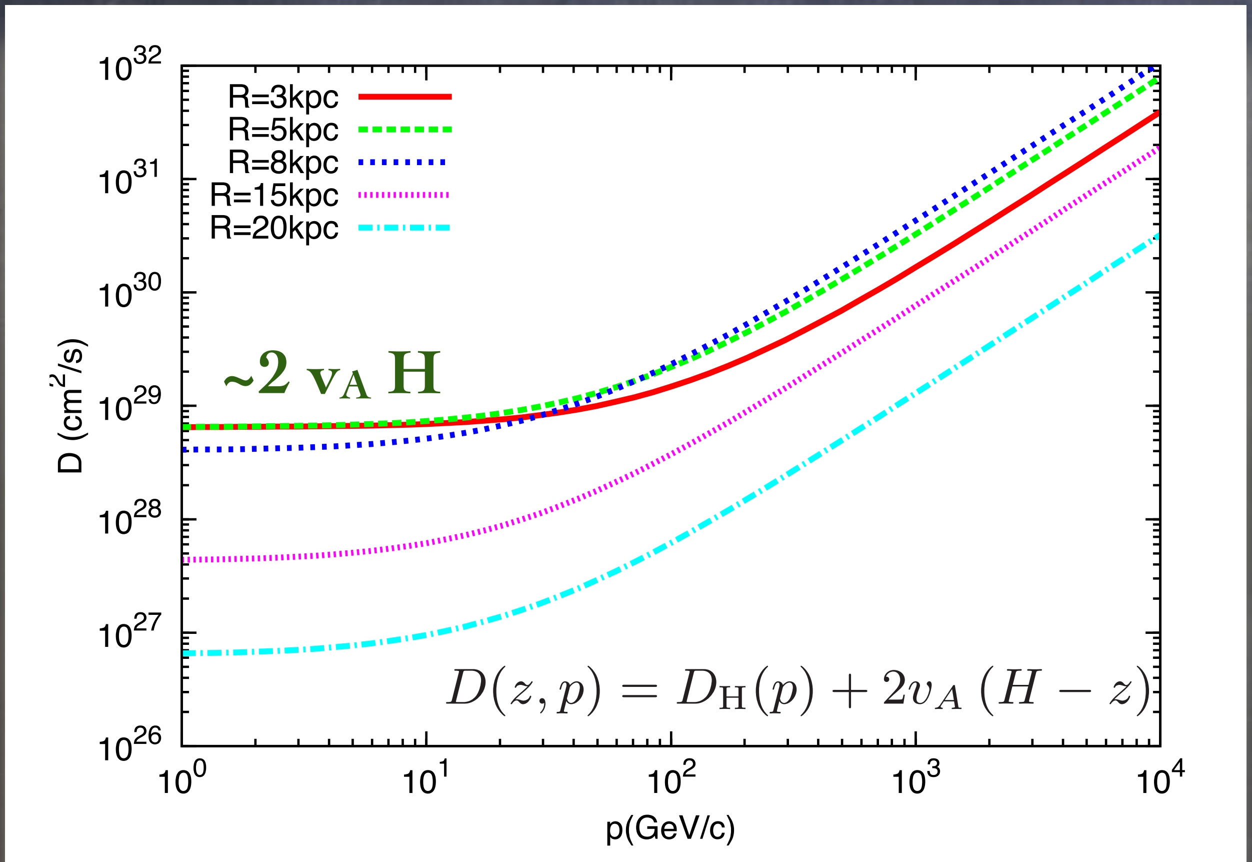
THE RADIAL DISTRIBUTION OF CR AS INFERRED FROM GAMMA RAY OBSERVATIONS IS TOO FLAT IN THE INNER GALAXY AND TOO STEEP IN THE OUTER GALAXY

$$f_{\rm SNR} \propto \left(\frac{R}{R_\odot}\right)^\alpha \exp\left(-\beta\frac{R-R_\odot}{R_\odot}\right)$$

DISTRIBUTION OF SNR (GREEN)

$$B_0(R>10\,{\rm kpc}) = \frac{B_\odot R_\odot}{R}\exp\left[-\frac{R-10\,{\rm kpc}}{d}\right]$$

ASSUMED B-FIELD AS FUNCTION OF R



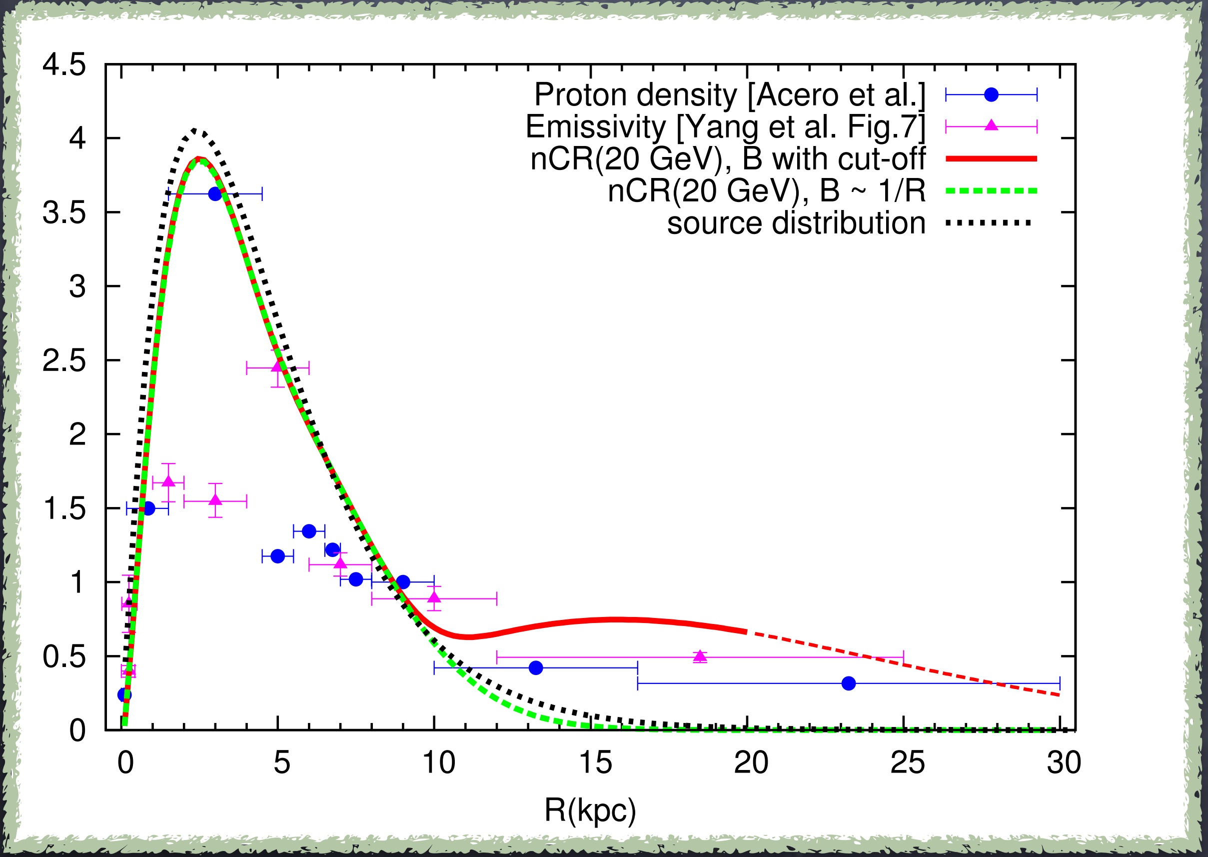
1. IN SELF-GENERATED MODELS A GENERIC FEATURE IS THE D(p) TENDS TO CONSTANT AT LOW p
2. THE CONSTANT IS ~ $2V_AH$
3. THE RELATIVE BALANCE BETWEEN ADVECTION AND DIFFUSION IS F(R)

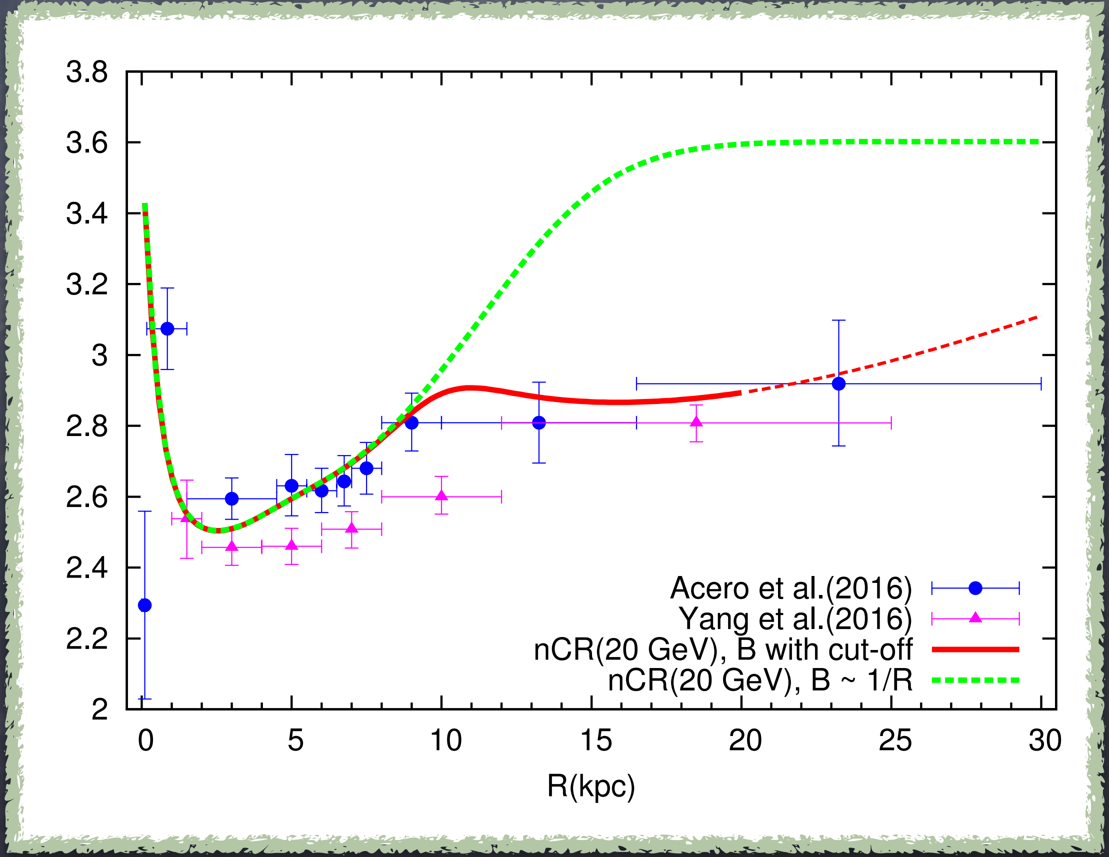
The CR Radial Gradient

The CR density as a function of the Galactocentric distance R is flatter than expected based upon source density, for large R

...But it has a peak in the central region of the Galaxy...

The spectrum is also harder in the central Galaxy than it is in the outskirt





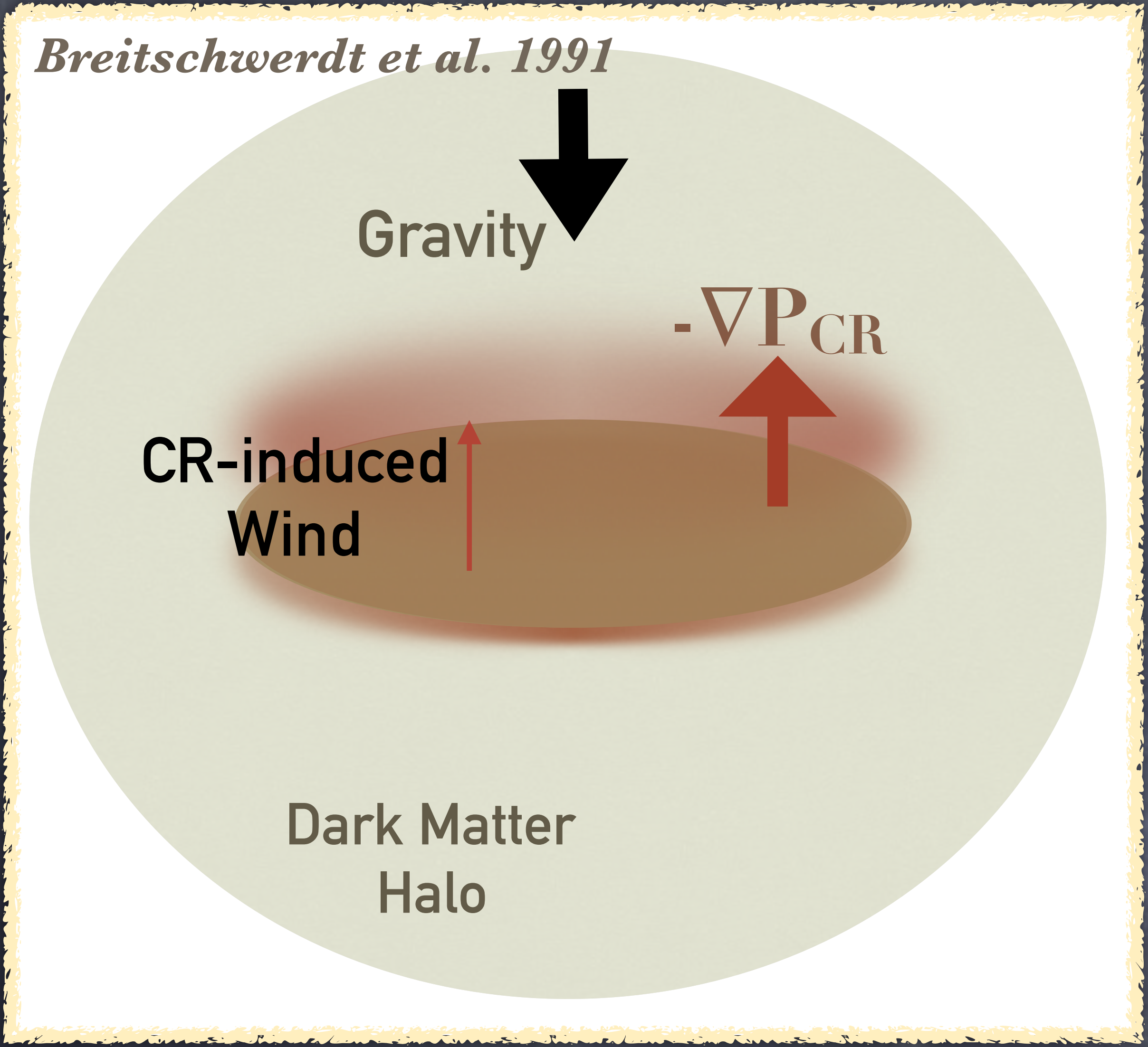
Recchia, PB & Morlino 2016

NON LINEAR COSMIC RAY TRANSPORT:

2) LAUNCHING OF CR INDUCED GALACTIC WINDS IN THE PRESENCE OF WAVE SELF-GENERATION

Recchia, PB & Morlino, 2016 MNRAS, 462, 4227
Recchia, PB & Morlino, in preparation, 2017

Cosmic Rays vs Gravity



The force exerted by CR may wins over gravity and a wind may be launched

$$\vec{\nabla}\cdot(\rho\vec{u}) = 0,$$

$$\rho(\vec{u}\cdot\vec{\nabla})\vec{u} = -\vec{\nabla}(P_g + P_c) - \rho\vec{\nabla}\Phi,$$

$$\vec{u}\cdot\vec{\nabla}P_g = \frac{\gamma_g P_g}{\rho}\vec{u}\cdot\vec{\nabla}\rho - (\gamma_g - 1)\vec{v_A}\cdot\vec{\nabla}P_c,$$

$$\vec{\nabla}\cdot\left[\rho\vec{u}\left(\frac{u^2}{2} + \frac{\gamma_g}{\gamma_g - 1}\frac{P_g}{\rho} + \Phi\right)\right] = -(\vec{u} + \vec{v}_A)\cdot\vec{\nabla}P_c,$$

$$\vec{\nabla}\cdot\left[(\vec{u} + \vec{v}_A)\frac{\gamma_c P_c}{\gamma_c - 1} - \frac{\overline{D}\vec{\nabla}P_c}{\gamma_c - 1}\right] = (\vec{u} + \vec{v}_A)\cdot\vec{\nabla}P_c,$$

$$\vec{\nabla}\cdot\vec{B} = 0$$

$$\vec{\nabla}\cdot\left[D\vec{\nabla}f\right] - (\vec{u} + \vec{v}_A)\cdot\vec{\nabla}f + \vec{\nabla}\cdot(\vec{u} + \vec{v}_A)\frac{1}{3}\frac{\partial f}{\partial \ln p} + Q = 0$$

Diffusion determined by self-generation at CR gradients balanced by local damping of the same waves

No pre-established diffusion coefficient and no pre-fixed halo size

PREVIOUS ATTEMPTS

Ipavich (1975): First treatment of CR induced winds (no dark matter, spherical symmetry, no diffusion, no kinetic CR, namely no spectra)

Breitschwerdt et al. (1991): First calculation of CR induced winds with dark matter and realistic geometry (diffusivity set to zero, no kinetic CR, namely no spectra; case of wave damping only treated for spherical symmetry)

Breitschwerdt et al. (1993): recognition of the importance of the launching region of the wind

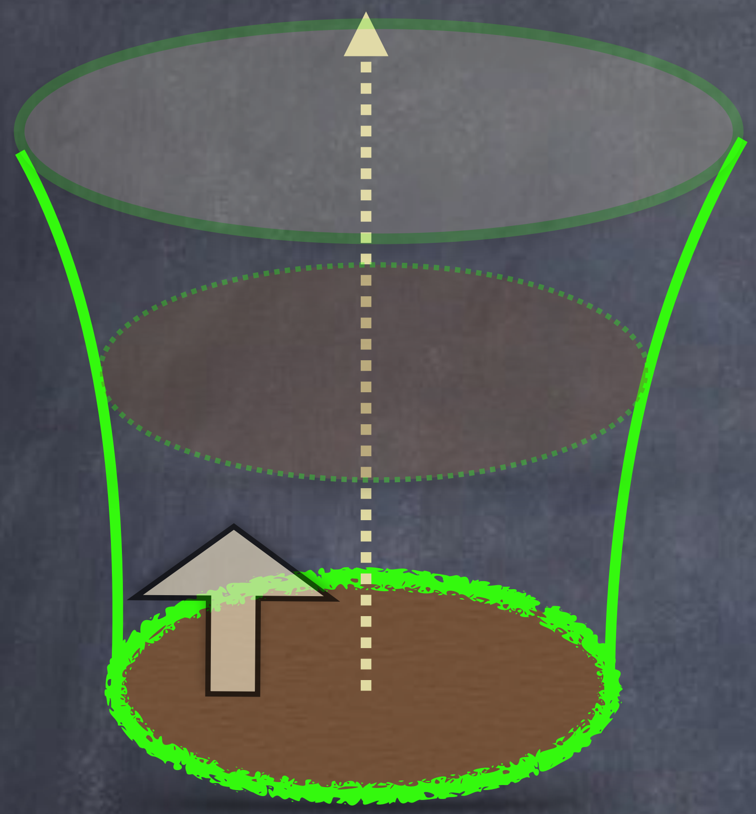
Ptuskin et al. (1997): adoption of Breitschwerdt (1991) method and simplified approach to the spectrum of CRs; inclusion of Galaxy rotation.

Dorfi & Breitschwert (2012): numerical hydro calculation, but no kinetic treatment of CRs

Everett et al. (2008): adoption of Breitschwerdt (1991) method and application to X-ray emission of the Galactic halo

Recchia et al. (2016): Generalization of the Breitschwerdt (1991) method to the case of diffusion, with realistic dark matter profile, with wave damping and detailed kinetic description of the CR transport

Cosmic Rays vs Gravity: CR driven winds



Aside from math, the Physics of the problem can be understood easily: There is a critical distance above (and below) the disc (which depends on particle energy) where diffusion turns into advection:

$$\frac{z^2}{D(p)} \simeq \frac{z}{u(z)} \to z_*(p) \propto p^{\delta/2} \qquad D(p) \sim p^{\delta}$$

Ptuskin et al. 1997

No fixed halo size H

$$f_0(p) = \frac{Q(p)}{2A_{disc}} \frac{H}{D(p)} \sim E^{-\gamma-\delta}$$

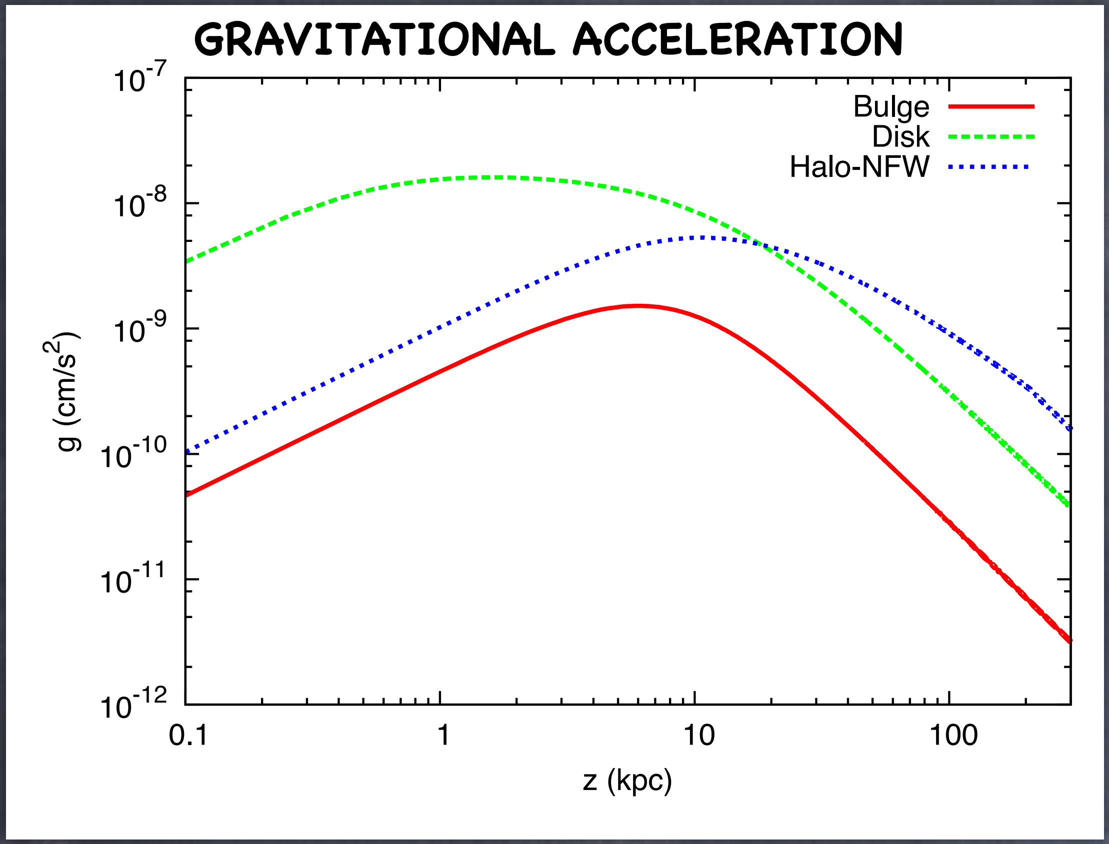
STANDARD CASE

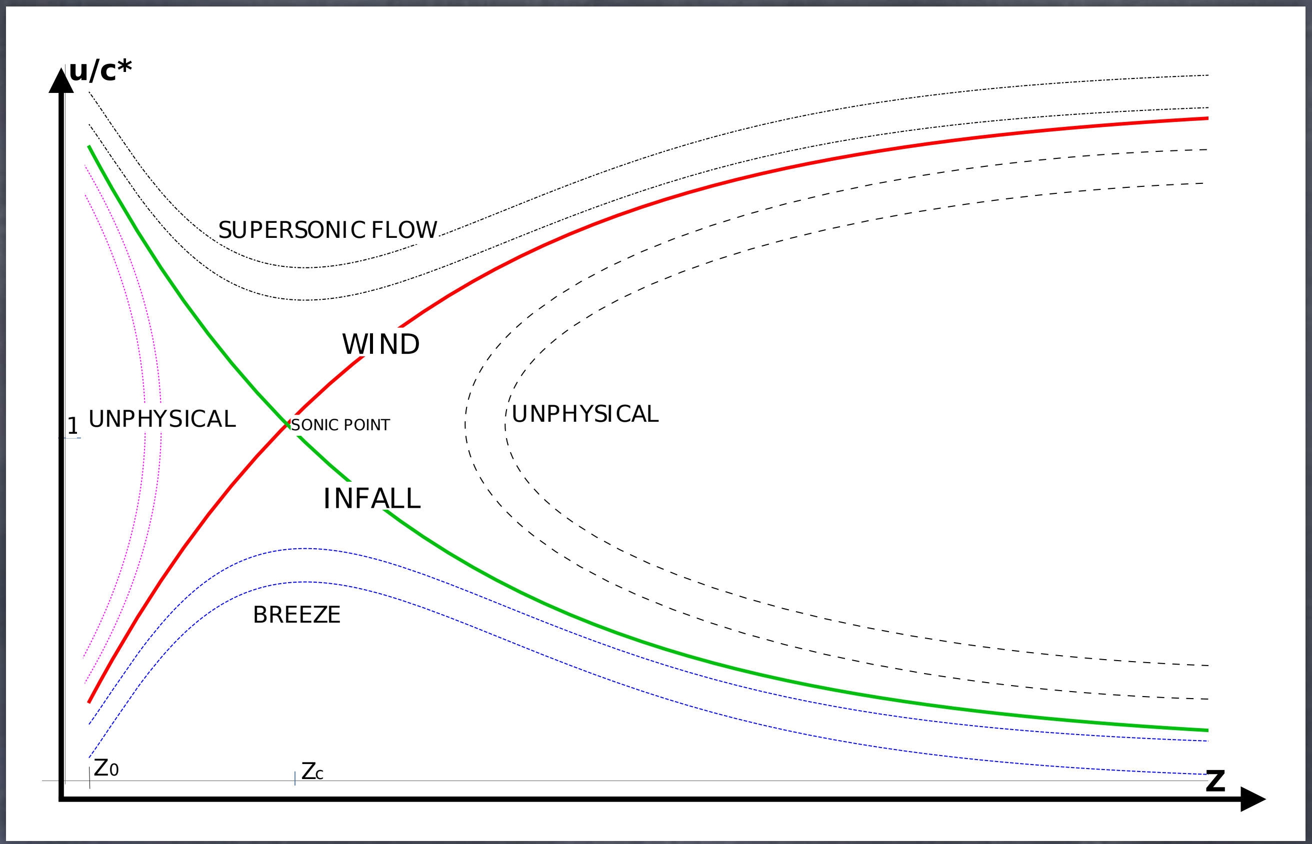
$$f_0(p) = \frac{Q(p)}{2A_{disc}} \frac{z_*(p)}{D(p)} \sim E^{-\gamma-\delta/2}$$

CR-INDUCED WIND WITH SELF-GENERATION

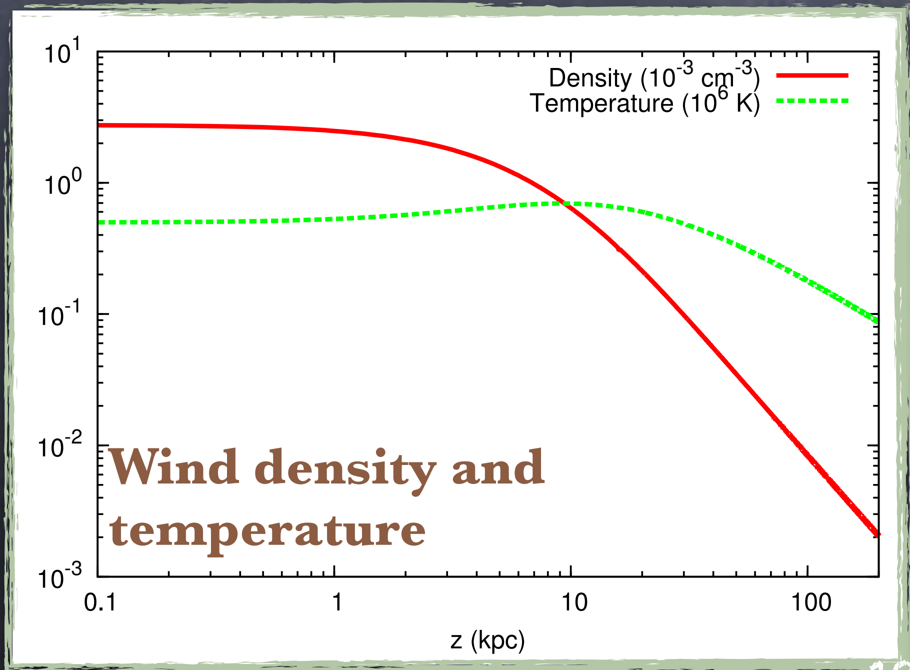
At high energy, the critical scale becomes larger than the size of the region where the geometry of the wind remains cylindrical, and a steepening of the spectrum should be expected

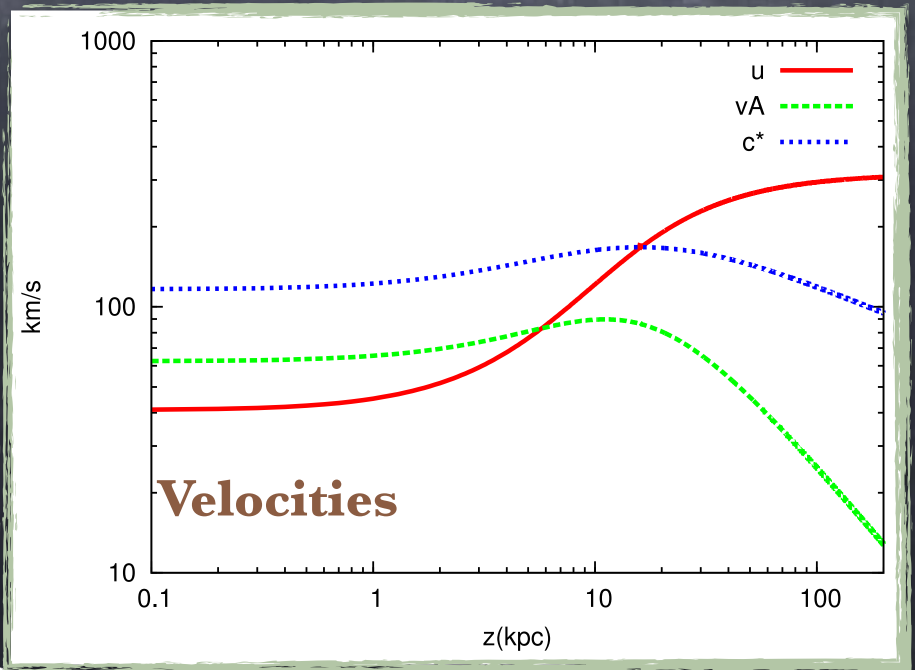
A LOOK AT THESE CR INDUCED WINDS



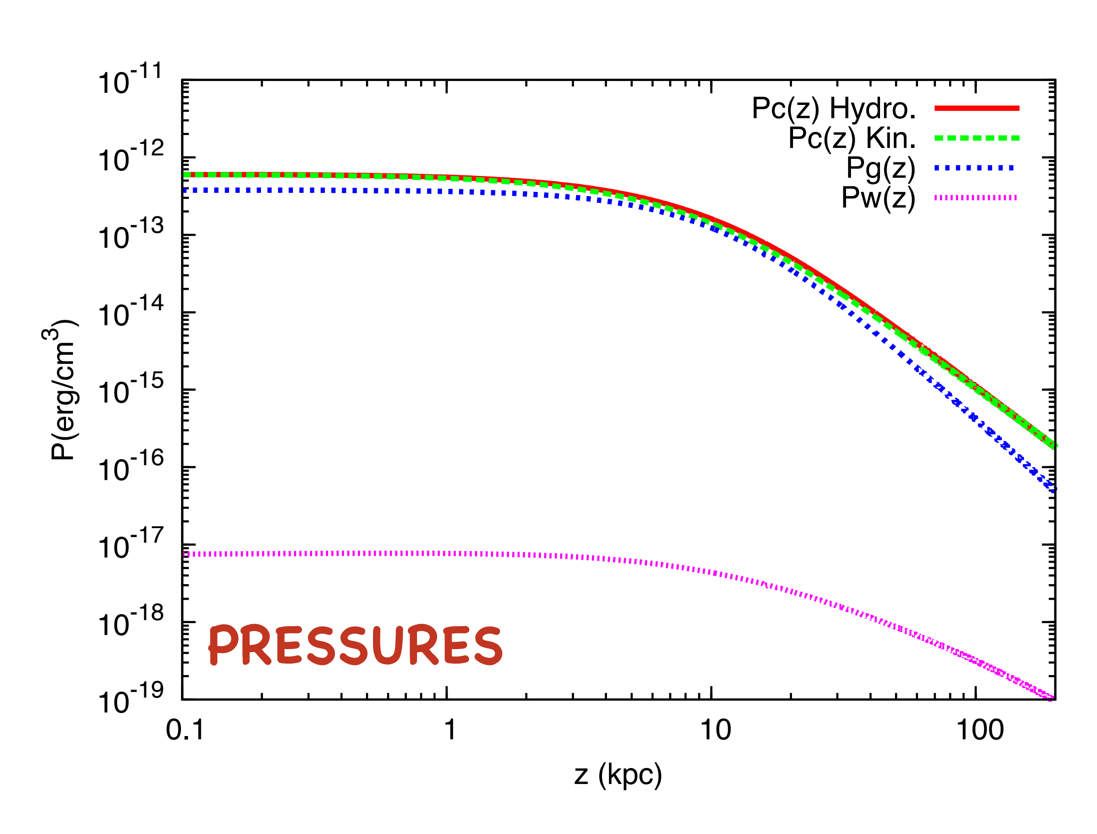


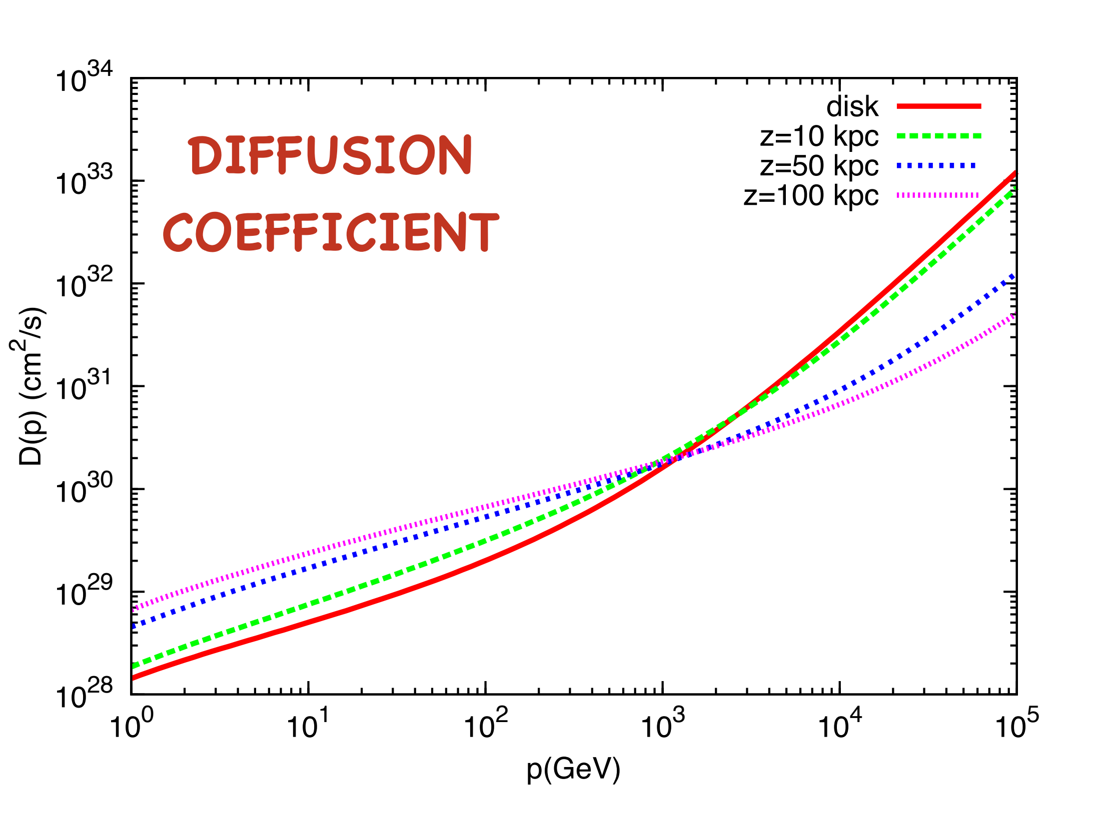
Recchia, PB & Morlino 2016

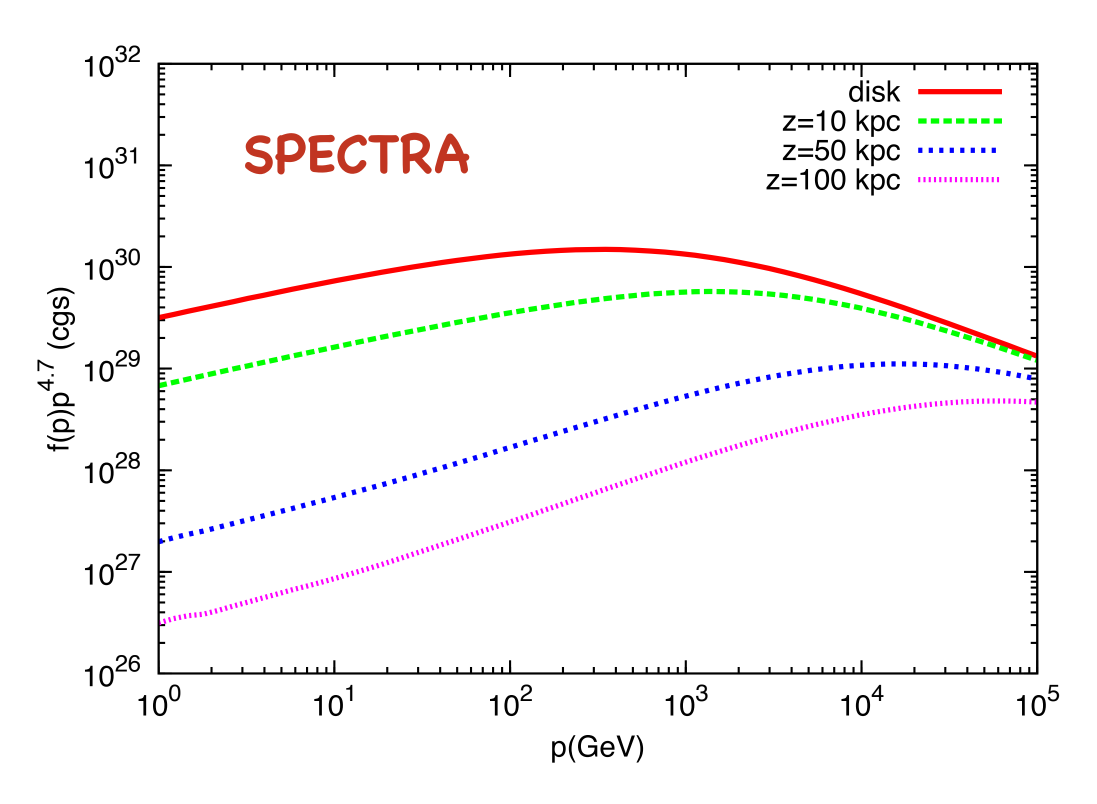




A LOOK AT THESE CR INDUCED WINDS







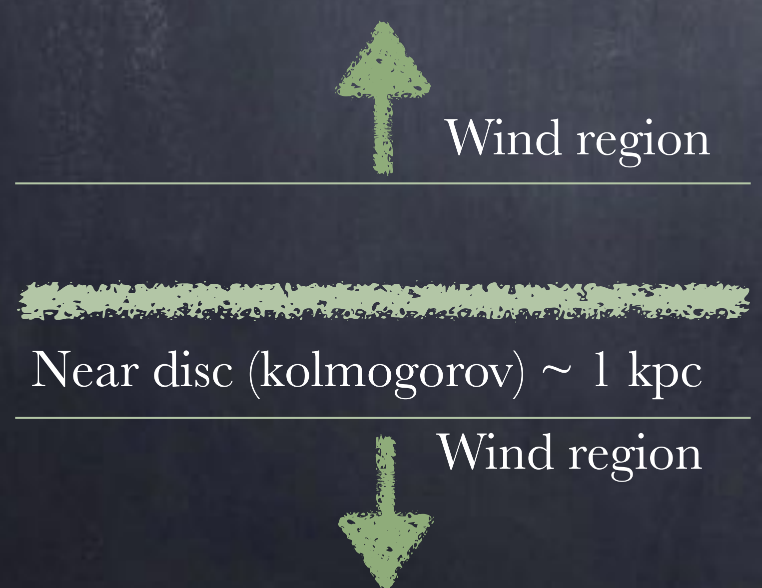
Wind solutions can be found, but they typically lead to CR spectra at the Earth that are quite unlike the observed ones...

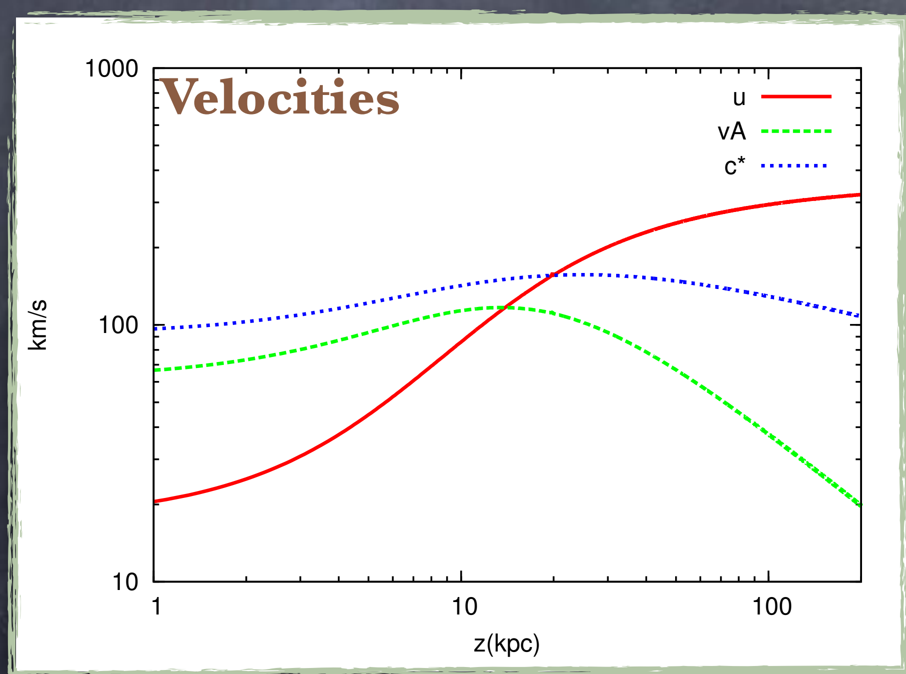
IMPORTANCE OF THE NEAR DISC REGION

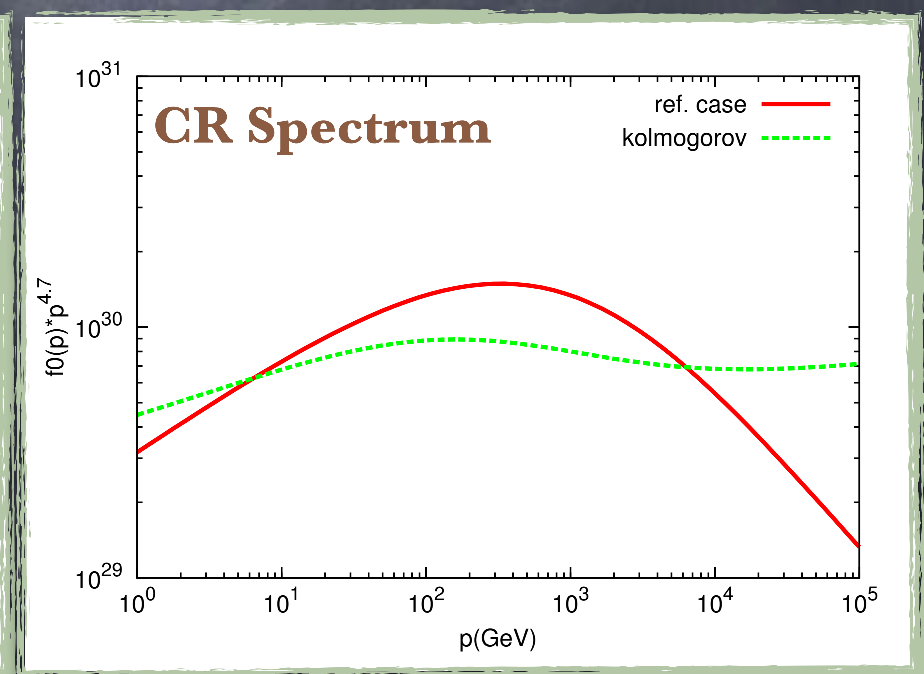
AS REALIZED BY Breitschwerdt et al. (1993) THE NEAR DISC REGION IS VERY CRITICAL TO FIND THE WIND SOLUTION

IT IS EVEN MORE CRITICAL TO DETERMINE THE SPECTRUM OF GALACTIC CR THAT CORRESPONDS TO A WIND SOLUTION, IN THAT THE NEAR DISC REGION CONNECTS HALO AND SOURCES (CRUCIAL IN A NON LINEAR PROBLEM)

IF ONE ASSUMES A NEAR DISC REGION WITH PRE-ASSIGNED D(E), FOR INSTANCE A LA KOLMOGOROV:







DEPENDENCE ON PARAMETERS

THE LAUNCHING OF WINDS DEPENDS ON SOME OF THE INPUT PARAMETERS OF THE PROBLEM:

1) SHAPE OF THE GRAVITATIONAL POTENTIAL
2) GEOMETRY OF THE OUTFLOW
3) PRESSURE CONDITIONS AT THE BASE
4) PRESENCE OF NEUTRAL H AT THE BASE

(Recchia, PB & Morlino, 2017, in preparation)

NON LINEAR COSMIC RAY TRANSPORT:

1) CR INDUCED INSTABILITIES AROUND GALACTIC SOURCES AND IMPLICATIONS FOR CR GRAMMAGE

D'Angelo, PB & Amato, PRD 2016
D'Angelo, PB, Amato & Morlino 2017, in prep

MOTIVATION

IT IS INTERESTING *per se*

SEVERAL ANOMALIES:

1) POSITRON EXCESS
2) ANTIPROTONS/PROTONS ~ ENERGY INDEPENDENT
3) PRODUCTION RATES OF Pbar and e^+ AS EXPECTED FROM PARTICLE PHYSICS (as if no energy dependent transport and no energy losses were present - Lipari 2016)

SOME AUTHORS HAVE SPECULATED THAT POSITRONS AND ANTIPROTONS ARE ALL PURELY SECONDARIES (Wawman, Cowsik, Lipari)

IS THERE ANY PHYSICAL IMPLEMENTATION OF THESE IDEAS THAT IS MORE THAN JUST FUN SPECULATION?

CR INDUCED INSTABILITIES AROUND GALACTIC SOURCES AND CR GRAMMAGE

On a scale of 1-2 coherence scales of the field, diffusion is about 1-dimensional

In the standard scenario, the time for escaping the near-source region is too small to imply a significant grammage —> Grammage is mainly accumulated through propagation in the whole Galaxy (dense disc+empty halo)

$$X(E) \sim 1.4 \frac{L^2}{D(E)} m_p n_{gas} c \approx 0.2 \; E_{GeV}^{-\delta} g/cm^2$$

CR INDUCED INSTABILITIES AROUND GALACTIC SOURCES AND CR GRAMMAGE

The CR density close to the source and the gradients that develop remain large for quite some time, hence the CR current becomes sufficient to excite resonant CR streaming instability — CR BECOME DIFFUSIVELY SELF-CONFINED

$$\frac{\partial f}{\partial t} + v_A \frac{\partial f}{\partial z} - \frac{\partial}{\partial z}\left[D(p,z,t)\frac{\partial f}{\partial z}\right] = q_0(p)\delta(z)\Theta(T_{SN}-t)$$

CR TRANSPORT EQUATION

ADVECTION WITH SELF-GENERATED ALFVEN WAVES

DIFFUSION COEFFICIENT IN SELF-GENERATED WAVES

$$D(p,z,t) = \frac{1}{3} r_L(p) v(p) \frac{1}{\mathcal{F}(k,z,t)}\Big|_{k=1/r_L(p)}$$

$$\frac{\partial \mathcal{F}}{\partial t} + v_A \frac{\partial \mathcal{F}}{\partial z} = (\Gamma_{CR} - \Gamma_D)\mathcal{F}$$

TRANSPORT EQUATION OF WAVES

This set of coupled non-linear equations can be solved numerically for CR distribution function and diffusion coefficient

ROLE OF ION-NEUTRAL DAMPING

IN THE PRESENCE OF PARTIALLY IONIZED GAS AROUND A SNR, CHARGE EXCHANGE BETWEEN IONS AND NEUTRALS DAMPS ALFVEN WAVES AT A RATE:

$$\Gamma_D(k) = \frac{\nu}{2}, \qquad k > \frac{\nu}{v_A}\left(1+\frac{n_i}{n_H}\right) = k_*$$

$$\Gamma_D(k) = \frac{k^2 v_A^2}{2\nu\left(1+\frac{n_i}{n_H}\right)}, \qquad k < \frac{\nu}{v_A}\left(1+\frac{n_i}{n_H}\right)$$

Kulsrud & Cesarsky 1971

$$\nu = n_H \langle v_{rel}\sigma_{ce}\rangle \approx 8.4\times 10^{-9}\ s^{-1}\left(\frac{n_H}{cm^{-3}}\right)$$

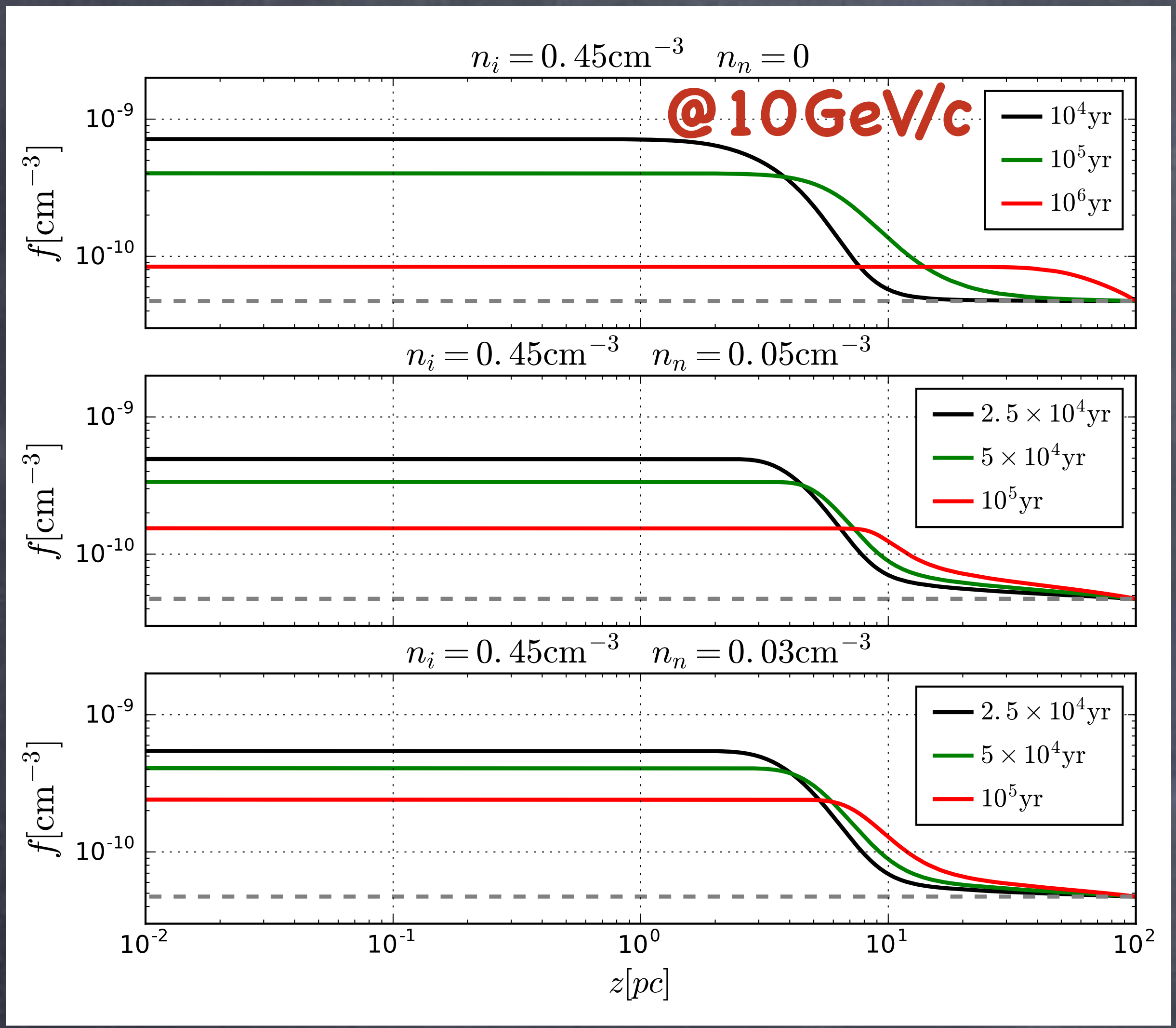
FOR TYPICAL VALUES OF GAS DENSITY 'IND' SEEMS TO BE IMPORTANT

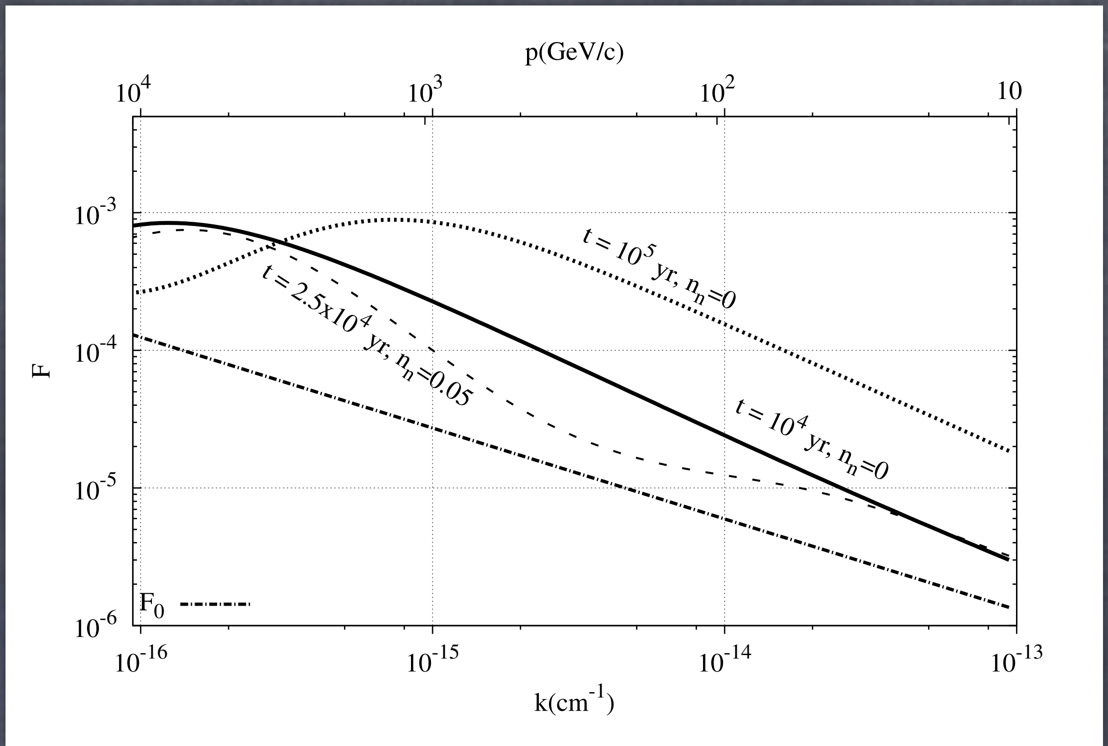
...BUT THERE ARE SOME CAVEATS:

MOST NEUTRAL GAS IN THE WIM IS IN THE FORM OF He — its charge exchange cross section is about 3 orders of magnitude smaller than for H

HOW LARGE IS THE FRACTION OF RESIDUAL NEUTRAL H AT 8000K?

RESULTS





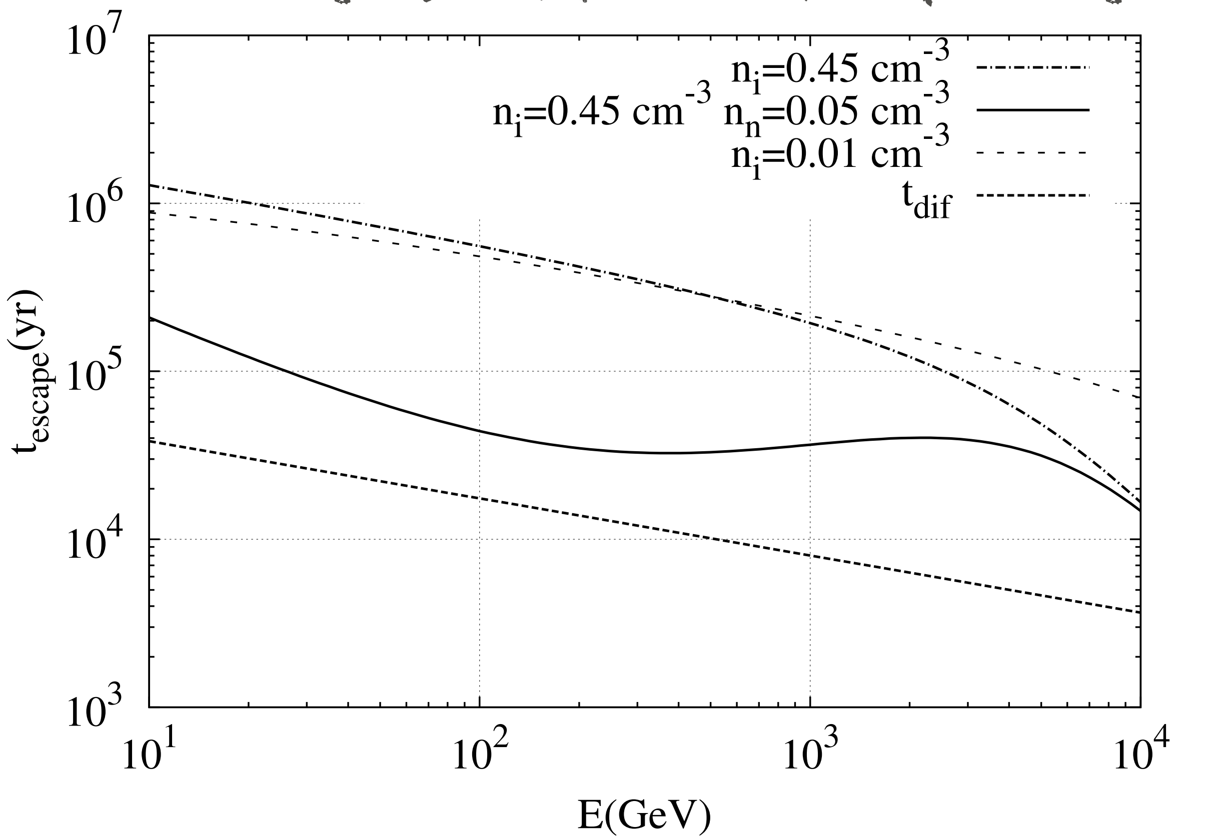
D'ANGELO + 2016

PARTICLES ARE SELF-TRAPPED AROUND THE SOURCE TO AN EXTENT THAT DEPENDS UPON THE LEVEL OF IONISATION OF THE ISM

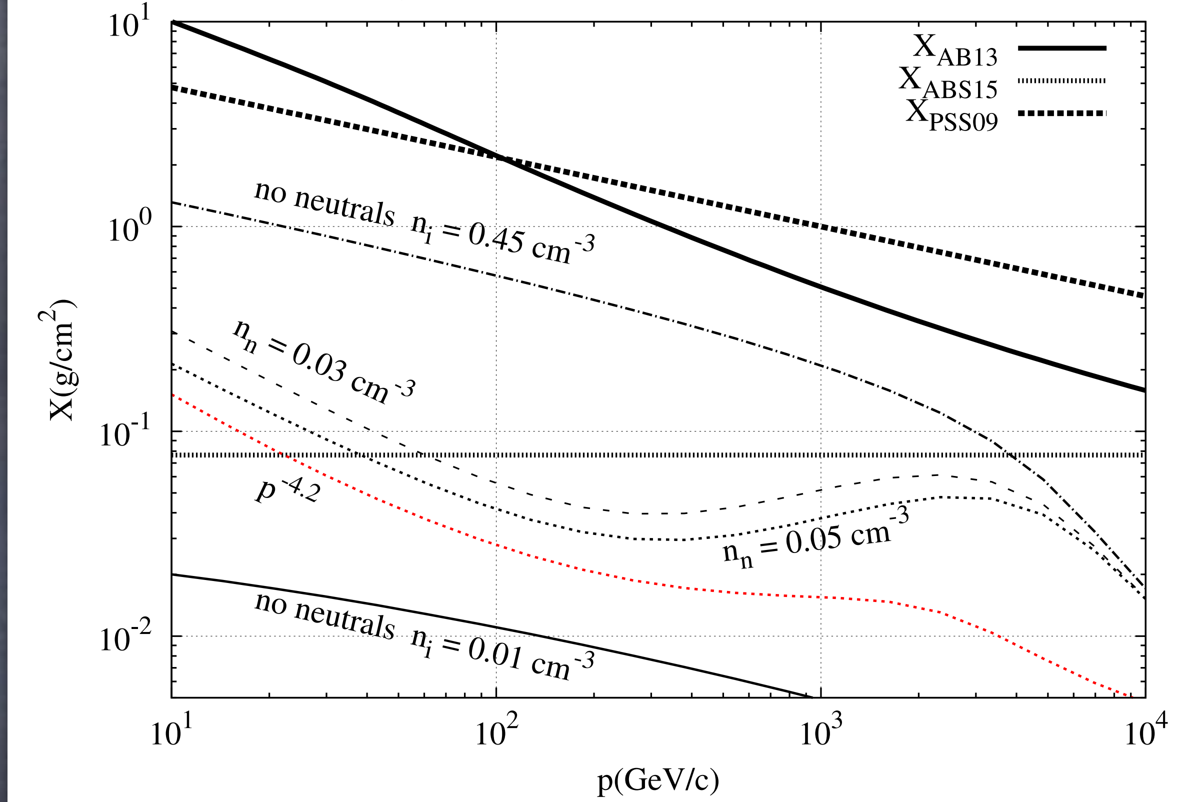
THE CONTRIBUTION OF THESE CR TO THE DIFFUSE GALACTIC GAMMA RAY EMISSION FROM THE DISC IS NOT NEGLIGIBLE (D'Angelo et al., in prep)

RESULTS

ESCAPE TIMES



GRAMMAGE



PARTICLES ARE CONFINED IN THE ISM AROUND A SNR FOR TIMES THAT LARGELY EXCEED THE STANDARD DIFFUSION TIME

THIS RESULT IS WEAKLY DEPENDENT UPON THE NEUTRAL DENSITY

THE ACCUMULATED GRAMMAGE IS NON NEGLIGIBLE IN THE ABSENCE OF NEUTRALS

AT HIGH ENOUGH ENERGY A RESIDUAL GRAMMAGE MAY BE PRESENT DUE TO THE VANISHING ROLE OF IND

CONCLUSIONS

1. THE STANDARD THEORY OF CR SCATTERING SPRINGS OUT OF THE SAME THEORETICAL CONSIDERATIONS THAT LEAD TO PREDICT WAVE GENERATION — CR TRANSPORT IS INTRINSICALLY NON LINEAR
2. THESE EFFECTS ARE HOWEVER IGNORED IN THE 'STANDARD MODELS'
3. OBSERVATIONALLY, SOME ANOMALIES FORCE US TO RECONSIDER THE STANDARD MODELS, LOOKING FOR SUBTLE PHYSICAL EFFECTS
4. NL EFFECTS NEAR SNR CAN CHANGE THE GRAMMAGE, TO AN EXTENT THAT DEPENDS ON THE FRACTION ON NEUTRAL H
5. NL GALACTIC CR TRANSPORT LEADS TO SEVERAL IMPLICATIONS (ADVECTION AT LOW E FITS VOYAGER, CHANGE OF SLOPE AT FEW HUNDRED GV)
6. CR CAN LAUNCH GALACTIC WINDS — IMPLICATIONS FOR SPECTRUM AND GALACTIC DYNAMICS