GRAN SASSO SCIENCE INSTITUTE
SCHOOL OF ADVANCED STUDIES
Scuola Universitaria Superiore

LECTURE 2
COSMIC RAY PROPAGATION

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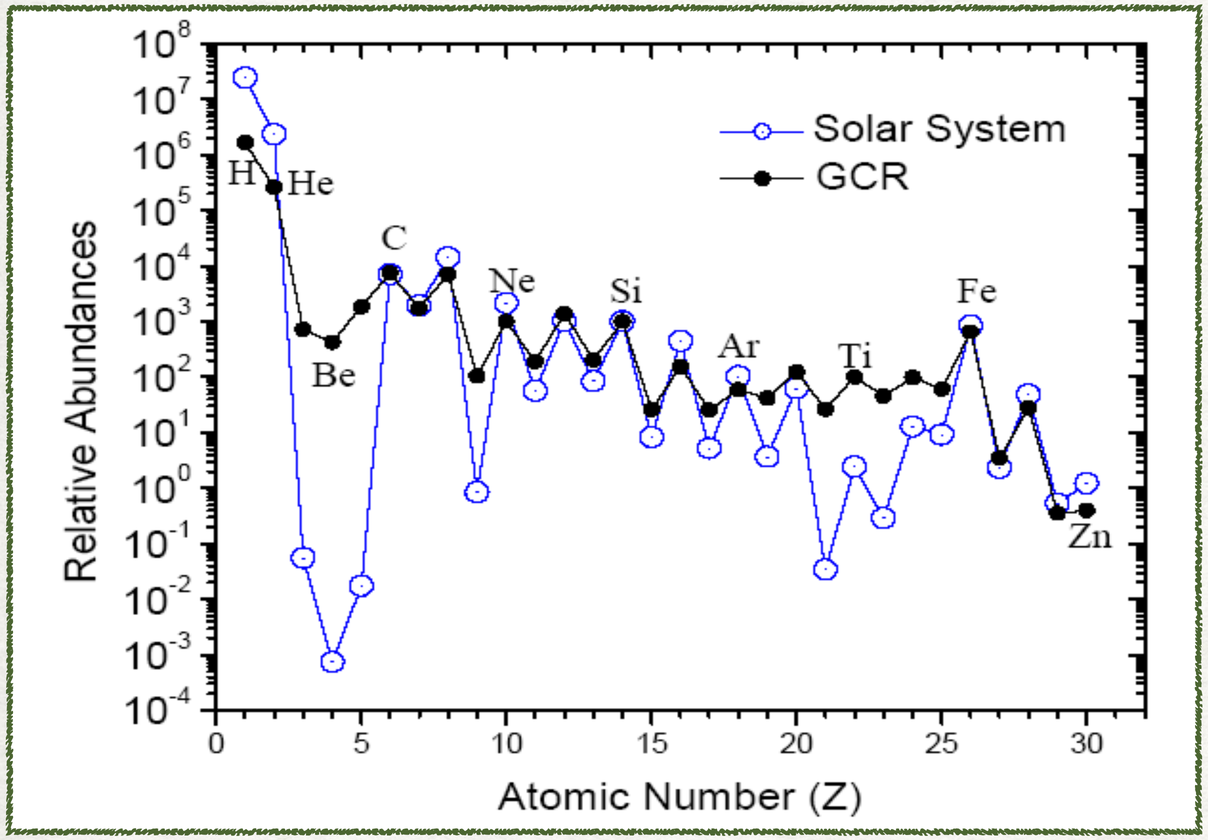
GRAN SASSO SCIENCE INSTITUTE, CENTER FOR ADVANCED STUDIES

Asiago School, January 15 2020

BASIC INDICATORS OF DIFFUSIVE TRANSPORT

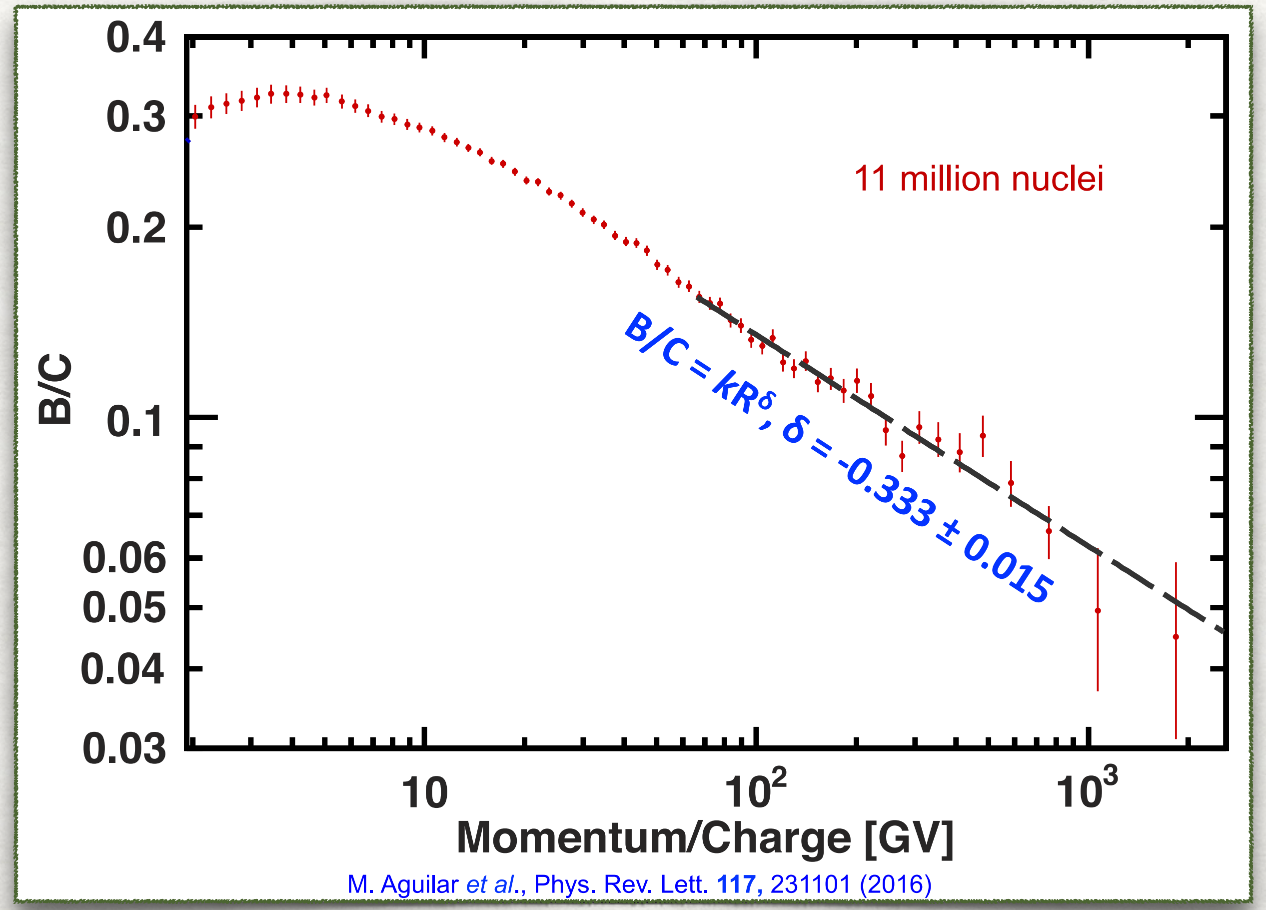


Measurements of the Boron and sub-iron elements in CRs show that CR live for tens of million years in the Galaxy

DIFFUSIVE TRANSPORT

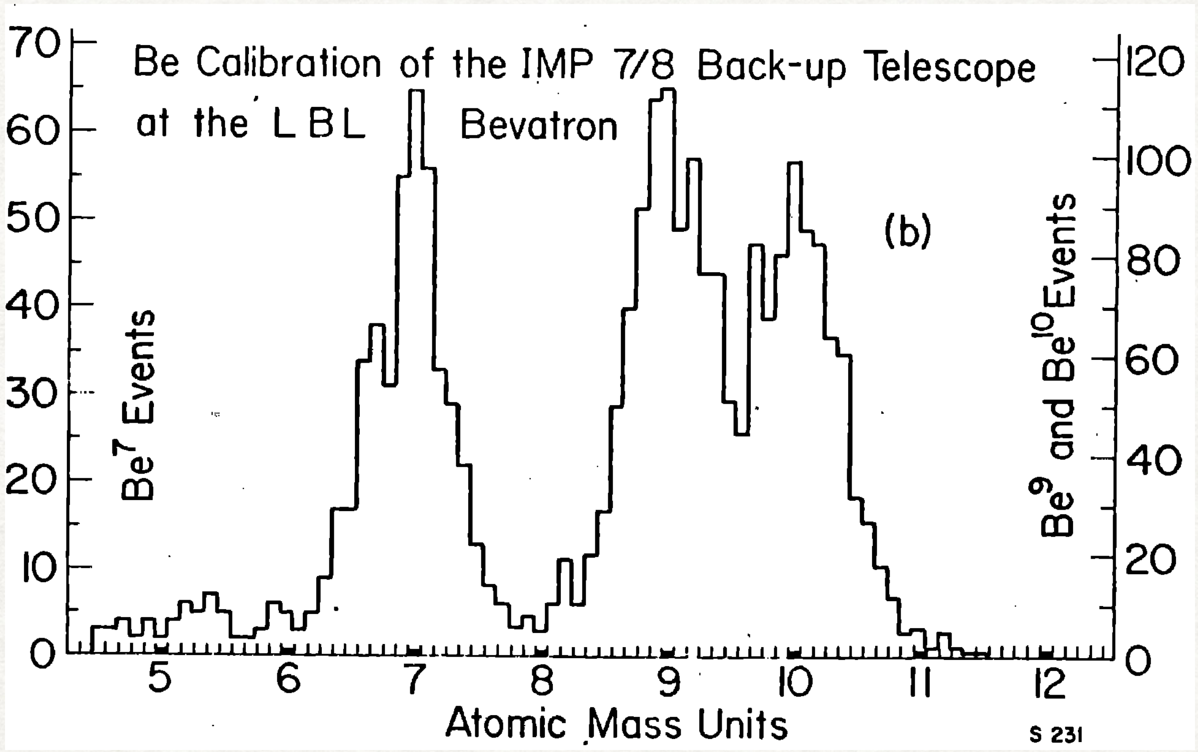
$$\sigma_{sp}(A) \approx 45A^{0.7} \text{ mb}$$

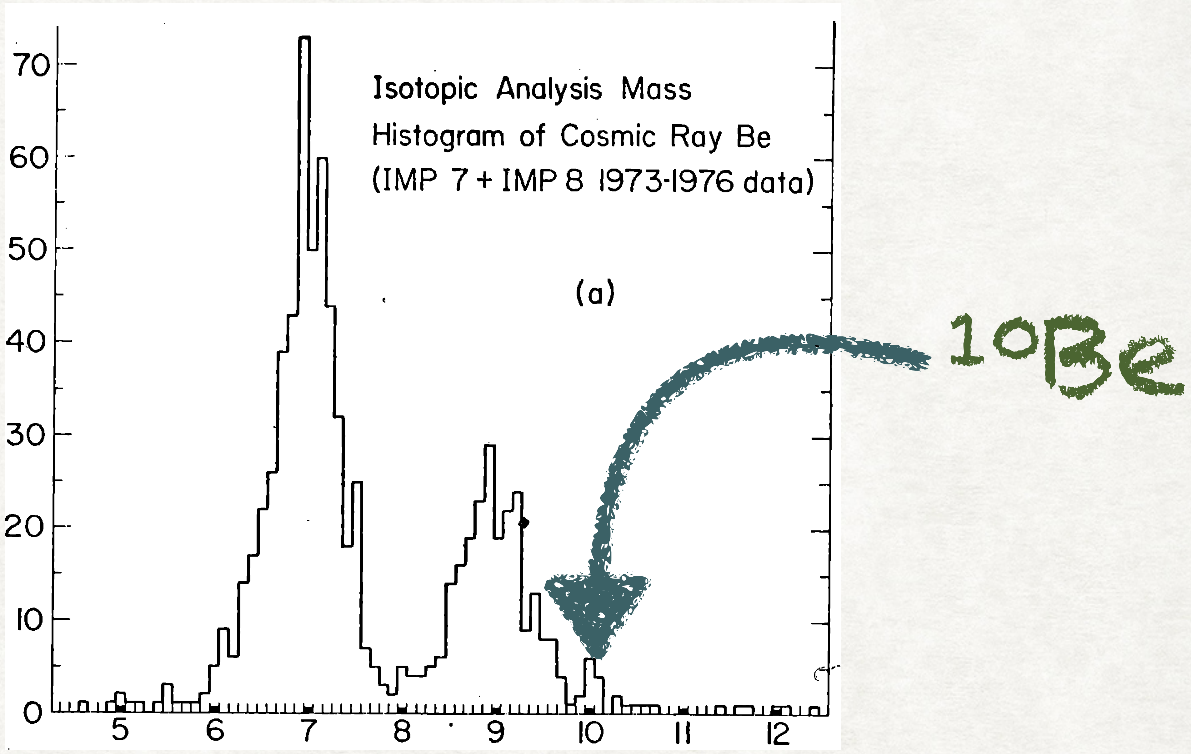
$$\tau_{sp} \approx [n_d(h/H)c\sigma_{sp}]^{-1} \approx 80 H_4 A_{12}^{-0.7} \text{ Myr}$$



BASIC INDICATORS OF DIFFUSIVE TRANSPORT

Garcia-Munoz et al. 1977



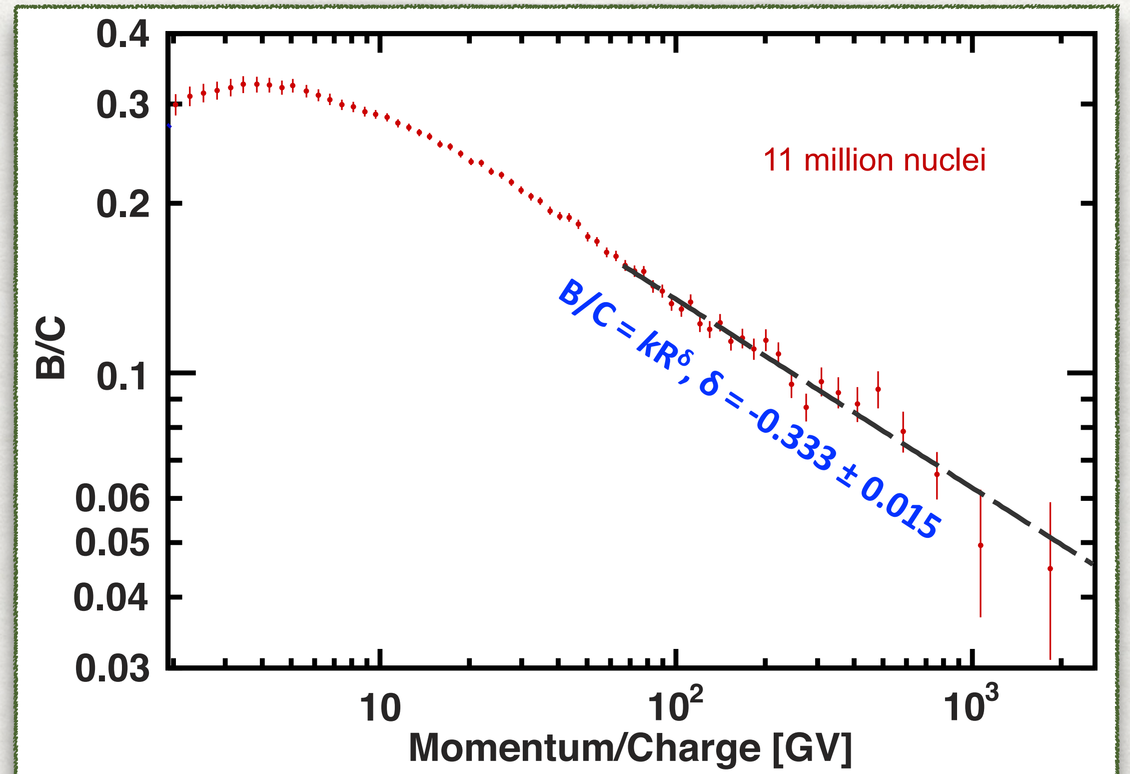


Be comes in three isotopes and ^{10}Be is unstable with a decay time of 15 Myr.

While in the Lab the three isotopes are roughly equally produced, in the CR we see the peak of ^{10}Be being much smaller —> information of decay vs production vs confinement

SECONDARY/PRIMARY: B/C

Evidence for CR diffusive transport



M. Aguilar *et al.*, Phys. Rev. Lett. **117**, 231101 (2016)

primary equilibrium

$$n_{pr}(E/n) \propto Q(E/n)\tau_{diff}(E/n)$$

secondary injection

$$q_{sec}(E/n) \approx n_{pr}(E/n)\sigma v n_{gas}$$

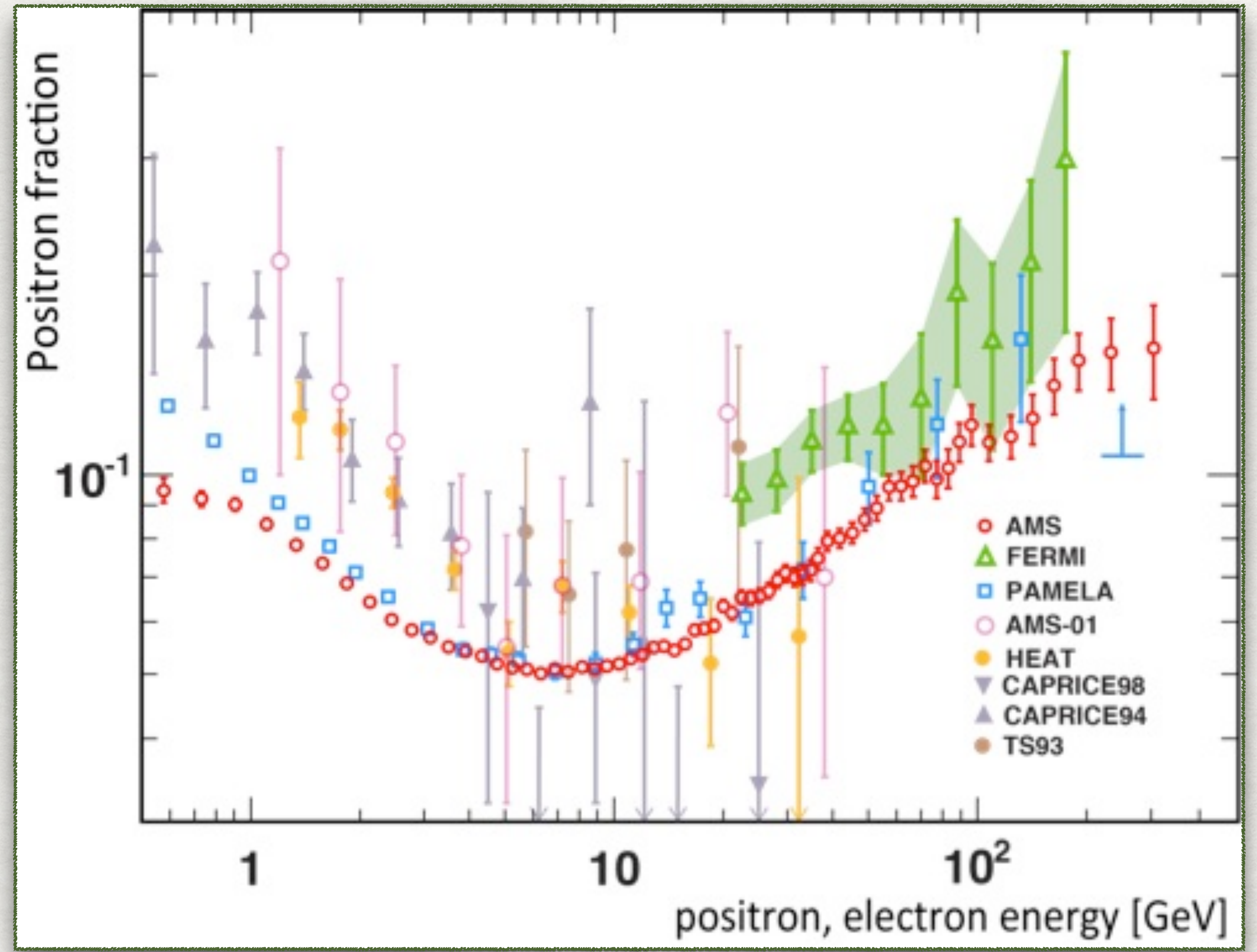
secondary equilibrium

$$n_{sec}(E/n) \approx q_{sec}(E/n)\tau_{diff}(E/n)$$

$$\frac{n_{sec}}{n_{pr}} \approx \frac{\sigma}{m_p}\left[v n_{gas} m_p \tau_{diff}\right]$$

GRAMMAGE: $X(E/n) \propto \tau_{diff}(E/n) \sim 1/D(E/n)$

SECONDARY/PRIMARY: POSITRON FRACTION



AMS-02 Coll. 2013

Reacceleration of secondary Pairs in old SNRs

PB 2009, PB & Serpico 2009; Mertsch & Sarkar 2009

Pulsar Wind Nebulae

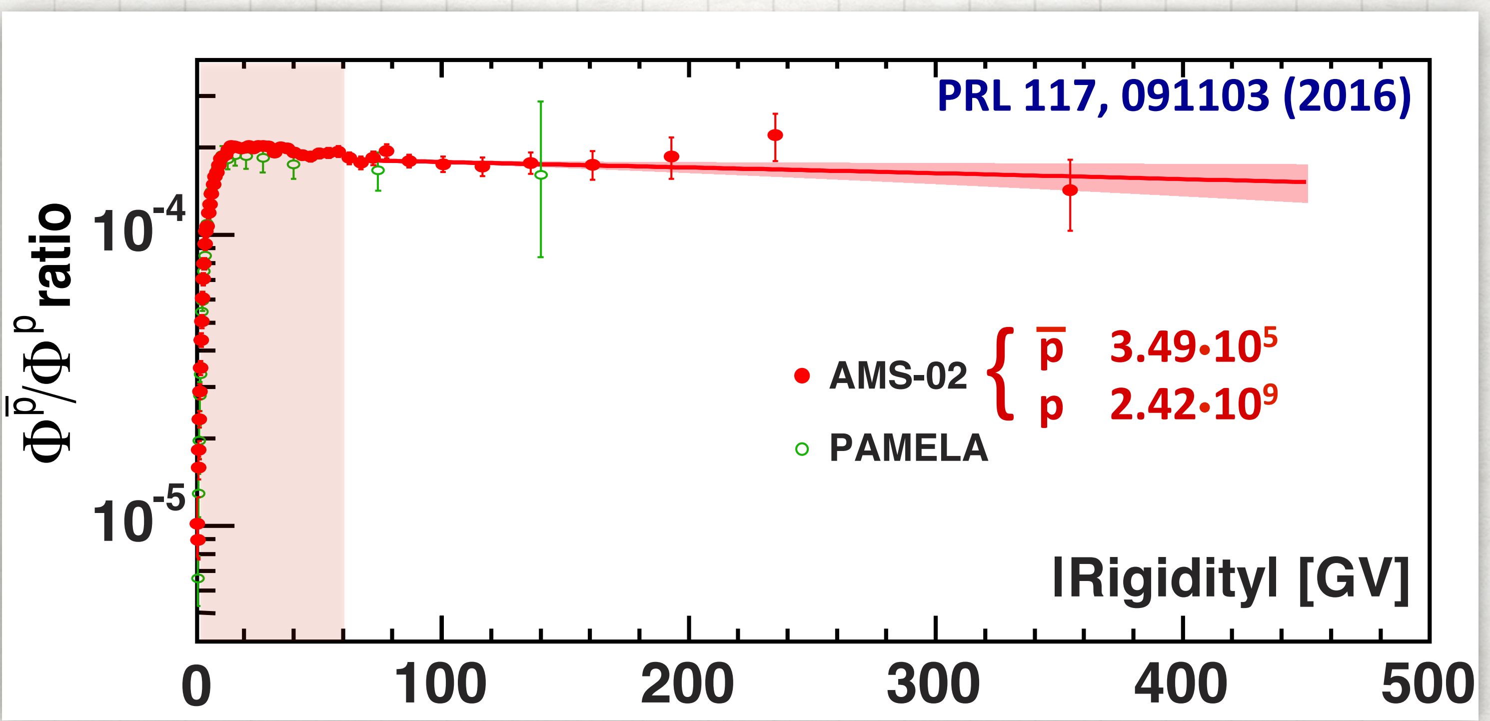
Hooper, PB & Serpico (2009); PB & Amato 2010

Dark Matter Annihilation

Difficult: high annihilation, Cross section, leptophilia, Boosting factor [Serpico (2012)]

SECONDARY/PRIMARY: ANTIPROTONS

- ANTIPROTONS ARE ALSO PRODUCED AS A RESULT OF CR INTERACTIONS
- THE IR SPECTRUM IS EXPECTED TO BE STEEPER THAN THAN OF PARENT PROTONS FOR THE SAME REASONS
- AMS-02 DATA SHOW A POSSIBLE ANOMALY, BUT NOT CLEAR AS YET (cross sections, astrophysics, ...)

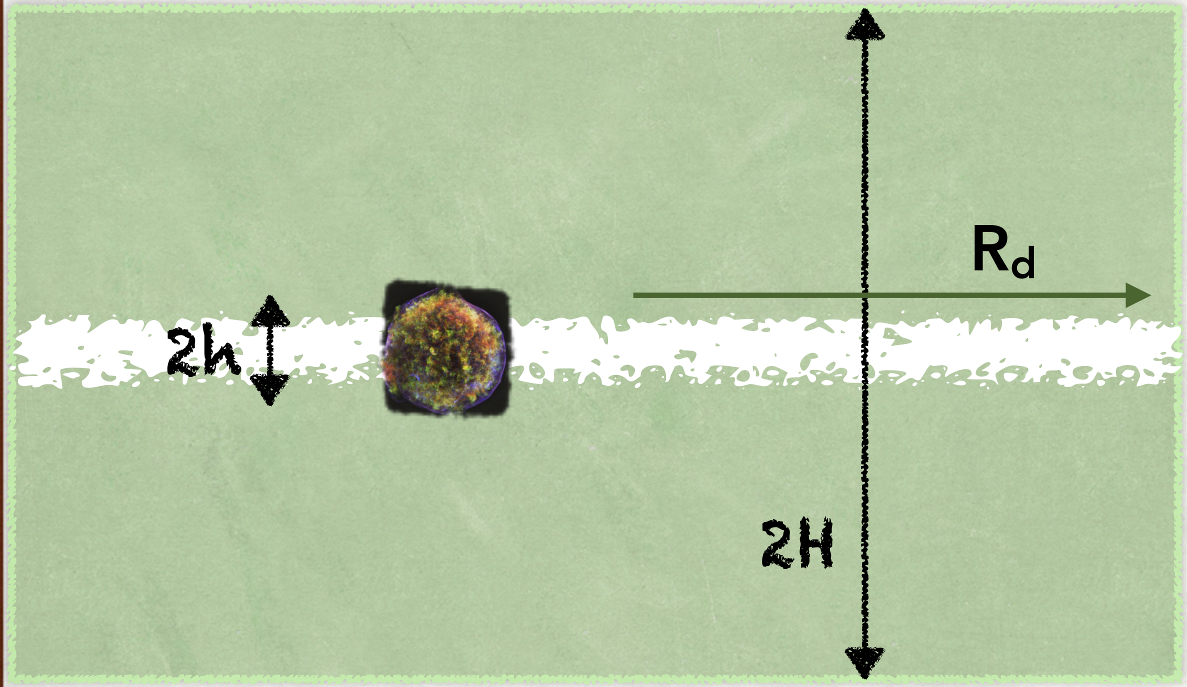


Notice that $e^+/e^- \sim 0.1$

B/C~0.1

pbar/p~10^{-4}

A TOY MODEL FOR OUR GALAXY



HALO ~ several kpc

DISC ~ 300 pc

Assumptions of the model:

1. *CR are injected in an infinitely thin disc*
2. *CR diffuse in the whole volume*
3. *CR freely escape from a boundary*

1 $$Q(p,z) = \frac{Q_0(p)}{\pi R_d^2}\delta(z)$$

2 $$-\frac{\partial}{\partial z}\left[D\frac{\partial f}{\partial z}\right] = Q(p,z)$$

3 $$f(z=H,p) = 0$$

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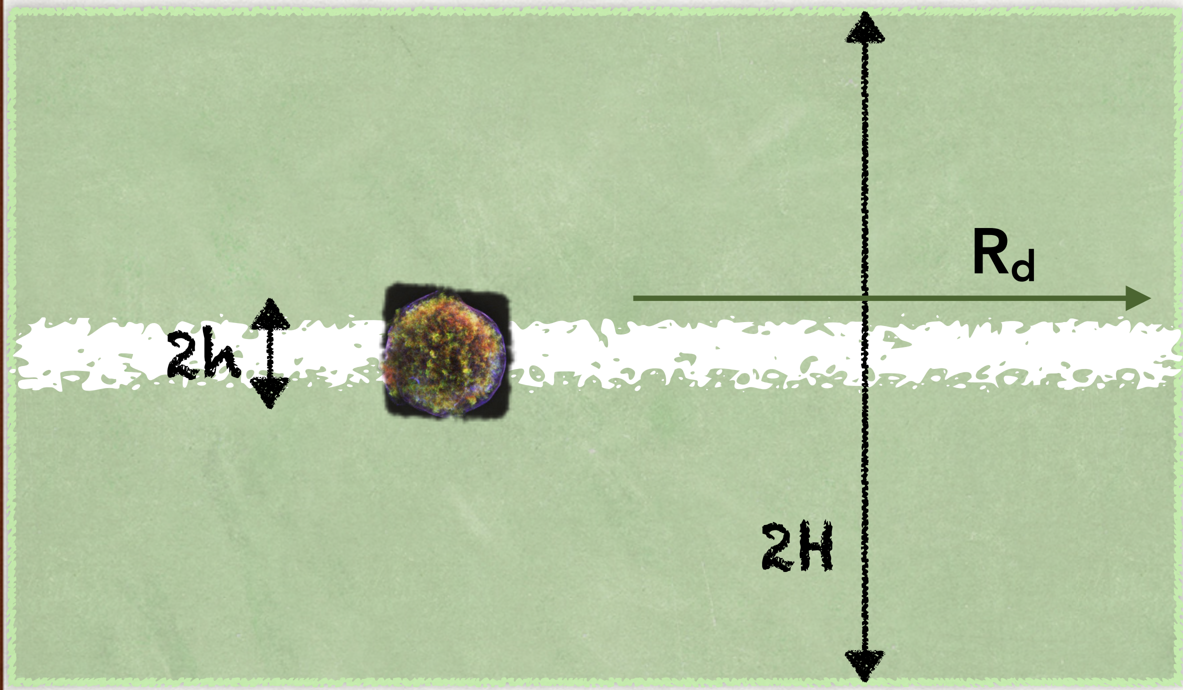

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For z≠0:

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

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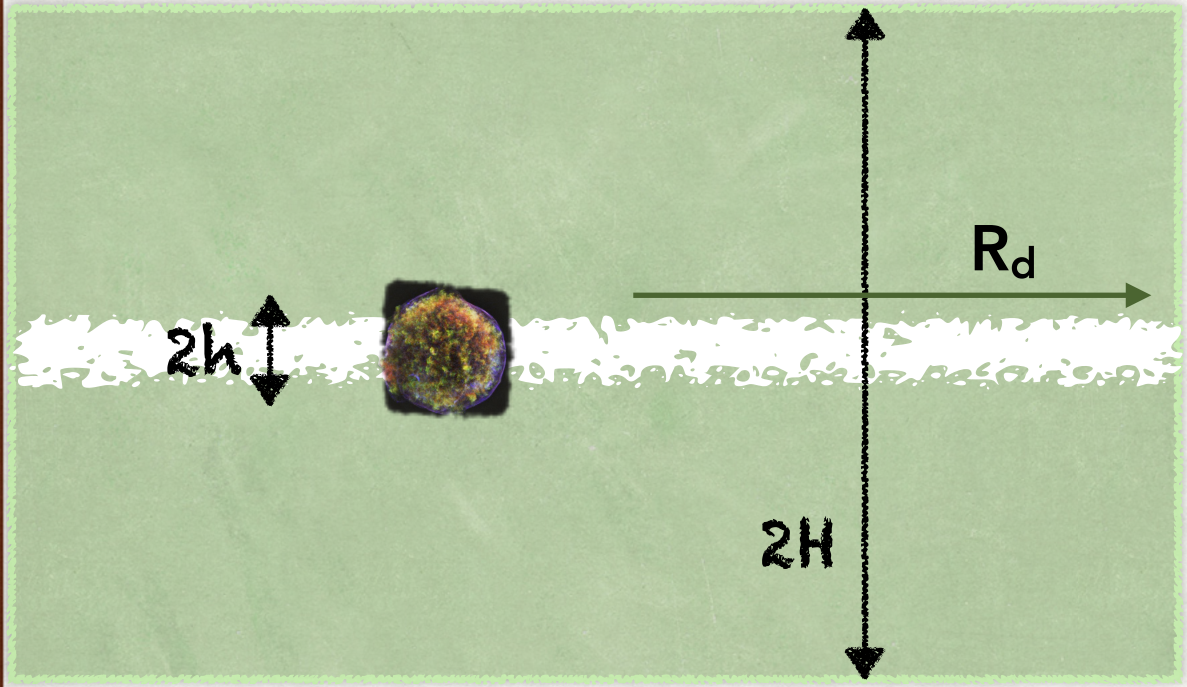

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$$D\frac{\partial f}{\partial z}|_{z=0^+} = -\frac{f_0}{H}$$

A TOY MODEL FOR OUR GALAXY

Let us now integrate the diffusion equation around z=0

$$-\frac{\partial}{\partial z}\left[D\frac{\partial f}{\partial z}\right] = \frac{Q_0(p)}{\pi R_d^2}\delta(z) \quad \Rightarrow \quad -2D\frac{\partial f}{\partial z}|_{z=0^+} = \frac{Q_0(p)}{\pi R_d^2}$$

and recalling that

$$D\frac{\partial f}{\partial z}|_{z=0^+} = -D\frac{f_0}{H} \quad \Rightarrow \quad f_0(p) = \frac{Q_0(p)}{2\pi R_d^2}\frac{H}{D} = \underbrace{\frac{Q_0(p)}{2\pi R_d^2 H}}_{\text{Rate of injection per unit volume}} \overbrace{\frac{H^2}{D}}^{\text{Diffusion Time}}$$

Since $Q_0(p) \sim p^{-\gamma}$ and $D(p) \sim p^{\delta}$
$f_0(p) \sim p^{-\gamma-\delta}$

A TOY MODEL FOR OUR GALAXY: ESCAPE FLUX

WHICH CR FLUX WOULD BE MEASURED BY AN OBSERVER OUTSIDE OUR GALAXY?

WE ALREADY ESTABLISHED THAT

$$D\frac{\partial f}{\partial z} = constant$$

BUT THIS IS EXACTLY THE FLUX ACROSS A SURFACE IN DIFFUSIVE REGIME:

$$\Phi_{esc}(p) = -D\frac{\partial f}{\partial z}|_{z=H} = -D\frac{\partial f}{\partial z}|_{z=0^+} = \frac{Q_0(p)}{2\pi R_d^2}$$

THE SPECTRUM OF COSMIC RAYS OBSERVED BY AN OBSERVER OUTSIDE OUR GALAXY IS THE SAME AS INJECTED BY SOURCES, NOT THE SAME AS WE MEASURE AT THE EARTH!

MEANING OF FREE ESCAPE BOUNDARY?

The physics of CR transport is as much regulated by diffusion as it is by boundary conditions (this is true for toy models as well as it is for GALPROP)

What does "free escape" mean? $f(z = H, p) = 0$

Conservation of flux at the boundary implies:

$$D \frac{\partial f}{\partial z}|_{z=H} = \frac{c}{3} f_{out}$$

$$D \frac{f_0}{H} = \frac{c}{3} f_{out} \to f_{out} = \frac{3D}{cH} f_0 \approx \frac{\lambda(p)}{H} f_0 \ll f_0$$

Beware that despite the great importance of this assumption we do not have any handle on what determines the halo size or weather the halo size depends on energy

A SIMPLE DESCRIPTION OF TRANSPORT OF NUCLEI

For nuclei of mass A, it is customary to introduce the flux as a function of the kinetic energy per nucleon E_k: $I_\alpha(E_k)dE_k = p^2 F_\alpha(p)\, v(p)\, dp$ which implies: $I_\alpha(E_k) = Ap^2 F_\alpha(p)$

$$-\frac{\partial}{\partial z}\left[D_\alpha \frac{\partial I_\alpha(E_k)}{\partial z}\right] + 2h_d n_d v(E_k)\sigma_\alpha \delta(z) I_\alpha(E_k) =$$

$$= 2Ap^2 h_d q_{0,\alpha}(p)\delta(z) + \sum_{\alpha'>\alpha} 2h_d n_d\, v(E_k)\sigma_{\alpha'\to\alpha}\delta(z) I_{\alpha'}(E_k)$$

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DIFFUSION

SPALLATION OF NUCLEI **α**

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INJECTION OF NUCLEI **α**

CONTRIBUTION TO NUCLEI **α** FROM SPALLATION OF NUCLEI **α'>α**

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INJECTION OF NUCLEI **α**

CONTRIBUTION TO NUCLEI **α** FROM SPALLATION OF NUCLEI **α'>α**

FOR SIMPLICITY THIS EQUATION DOES NOT CONTAIN SOME LOSS TERMS (IONIZATION), ADVECTION AND SECOND ORDER FERMI ACCELERATION IN ISM

ALL THESE EFFECTS MAY BECOME IMPORTANT AT E<10 GeV/nucleon

PRIMARY NUCLEI

$$-\frac{\partial}{\partial z}\left[D_\alpha \frac{\partial I_\alpha(E_k,z)}{\partial z}\right] + 2h_d n_d v(E_k)\sigma_\alpha \delta(z) I_\alpha(E_k) = \; 2Ap^2 h_d q_{0,\alpha}(p)\delta(z)$$

Formally similar to the equation for protons but with **spallation** taken into account

Technically the equation is solved in the same way:

1) *consider z>0 (or z<0) and then*
2) *integrate around z=0 between 0^- and 0^+*

1 $$D_\alpha \frac{\partial I_\alpha}{\partial z} = constant \rightarrow I_\alpha = I_{0,\alpha}\left(1 - \frac{z}{H}\right)$$ with free escape boundary condition

2 $$-D_\alpha \frac{\partial I_\alpha}{\partial z}|_{z=0} = -h_d n_d v \sigma_\alpha I_{0,\alpha} + Ap^2 h_d Q_{0,\alpha}(p)$$

PRIMARY NUCLEI

Injection X escape time

$$I_{0,\alpha}(E_k) = \frac{\frac{N_{inj,\alpha} R_{SN}}{2\pi R_{disc}^2 H} \frac{H^2}{D_\alpha}}{1 + \frac{X(E_k)}{X_\alpha}}$$

Flux of nuclei of type a

$$X(E_k) = n_d \left(\frac{h}{H}\right) m_p v \frac{H^2}{D_\alpha}$$

Grammage traversed by nuclei of type a

$$X_\alpha = \frac{m_p}{\sigma_\alpha}$$

Critical grammage for nuclei of type a

For $X \ll X_\alpha$ the equilibrium spectrum is the standard $E_k^{-\gamma-\delta}$

For $X \gg X_\alpha$ the equilibrium spectrum reproduces the injection spectrum $E_k^{-\gamma}$

SECONDARY NUCLEI - CASE OF B/C

$$-\frac{\partial}{\partial z}\left[D_\alpha \frac{\partial I_B}{\partial z}\right] + 2h_d n_d v \sigma_B \delta(z) I_B = 2h_d n_d\, \sigma_{CB} v I_C \delta(z) + 2h_d n_d\, \sigma_{OxB} v I_{Ox} \delta(z)$$

Destruction of B

Production of B from carbon spallation

Production of B from oxygen spallation

Following the same strategy as in the previous cases one obtains easily:

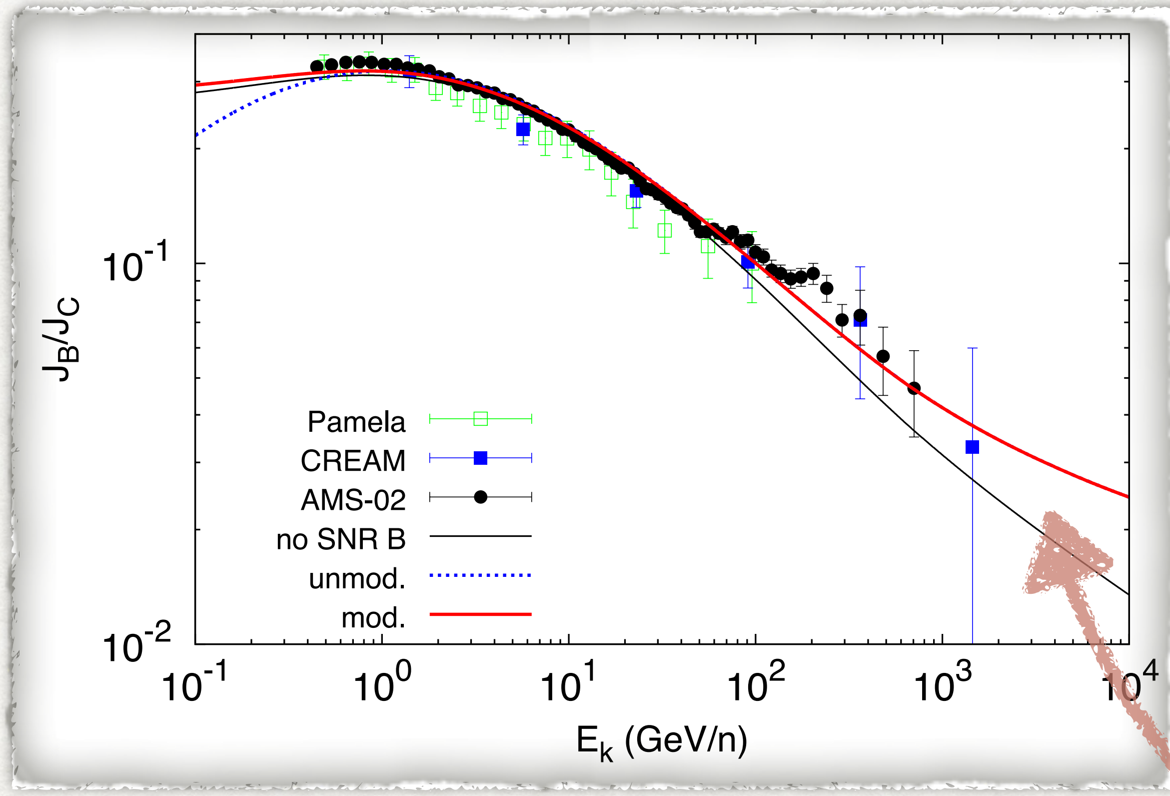
$$I_{B,0}(E_k) = \frac{I_{C,0}(E_k)\frac{X(E_k)}{X_{cr,CB}}}{1+\frac{X(E_k)}{X_{cr,B}}} + \frac{I_{Ox,0}(E_k)\frac{X(E_k)}{X_{cr,OxB}}}{1+\frac{X(E_k)}{X_{cr,B}}}$$

which reflects in the following B/C ratio:

$$\boxed{\frac{I_{B.0}(E_k)}{I_{C,0}(E_k)} = \frac{\frac{X(E_k)}{X_{cr,CB}}}{1+\frac{X(E_k)}{X_{cr,B}}} + \frac{I_{Ox,0}(E_k)}{I_{C,0}(E_k)}\frac{\frac{X(E_k)}{X_{cr,OxB}}}{1+\frac{X(E_k)}{X_{cr,B}}}}$$

AT E>100 GeV THE B/C RATIO SCALES AS $X(E_K)$ NAMELY AS $1/D_\alpha$ NAMELY WE CAN MEASURE THE SLOPE OF D(E) FROM THE ENERGY DEPENDENCE OF B/C

CAVEATS AND COMMENTS



1) THIS CONCLUSION HOLDS ONLY AT ENERGIES WELL ABOVE 50-100 GeV/n BECAUSE AT LOW E_k ADDITIONAL PHYSICS (ADVECTION, 2nd ORDER FERMI IN ISM, SPALLATION, SOLAR MODULATION)

2) BUT… AT HIGH ENERGIES THERE IS: GRAMMAGE IN THE SOURCES, GRAMMAGE AROUND THE SOURCES, ACCELERATION OF SECONDARIES, … **so be careful!!!**

A simple instance… the grammage accumulated by CR while trapped downstream of a supernova shock can be estimated as:

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

DECAY OF UNSTABLE ISOTOPES

THIS IS THE FIRST CASE WE MEET WHERE THE SOURCE OR LOSS TERM IS NOT IN THE FORM OF A DELTA FUNCTION (Z): THE DECAY OCCURS EVERYWHERE

$$-\frac{\partial}{\partial z}\left[D_a\frac{\partial f_a}{\partial z}\right]+v_A\frac{\partial f_a}{\partial z}-\frac{dv_A}{dz}\frac{p}{3}\frac{\partial f_a}{\partial p}$$

$$+\frac{1}{p^2}\frac{\partial}{\partial p}\left[p^2\left(\frac{dp}{dt}\right)_{a,\mathrm{ion}}f_a\right]+\frac{\mu v(p)\sigma_a}{m}\delta(z)f_a+\frac{f_a}{\hat{\tau}_{d,a}}$$

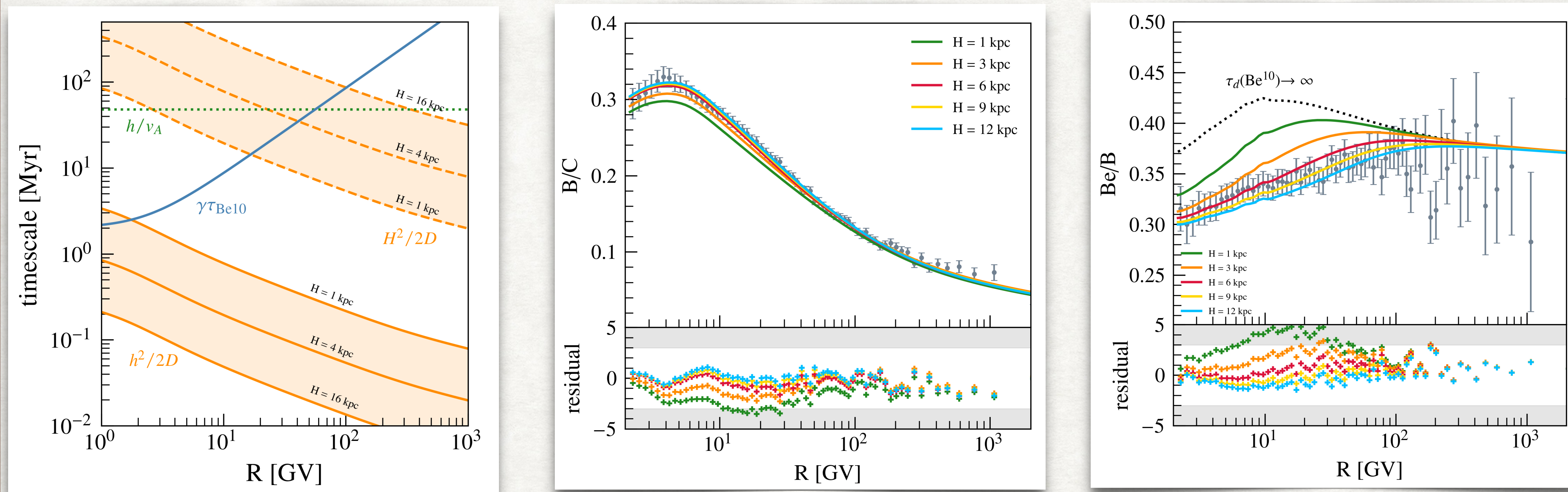
$$=2h_d q_{0,a}(p)\delta(z)+\sum_{a'>a}\frac{\mu\, v(p)\sigma_{a'\to a}}{m}\delta(z)f_{a'}+\sum_{a'>a}\frac{f_{a'}}{\hat{\tau}_{d,a'}}$$

TWO MAJOR CHANGES:

1) ^{10}Be decays on a time scale $\gamma\tau_d$ that at some high E becomes longer than $H^2/D(E)$

2) ^{10}Be decays mainly into ^{10}B so that it changes the abundance of stable elements

DECAY OF UNSTABLE ISOTOPES



THE DECAY OF 10Be SHOWS A PREFERENCE FOR RELATIVELY LARGE HALO SIZES

H>6 kpc

NON LINEAR DIFFUSION

The CR gradient excites Alfven waves at a rate:

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

$$D(p) = \frac{1}{3} r_L(p) v \frac{1}{\mathcal{F}}$$

$\sim f_0/H$

In Nature we expect that f(p,z) and D(p,z) determine each other... THEY ARE NOT INDEPENDENT QUANTITIES!

Interesting: WHEN REQUIRING $p^2 f(p) \sim p^{-2.7}$ one gets for free $D(p) \sim p^{0.7}$

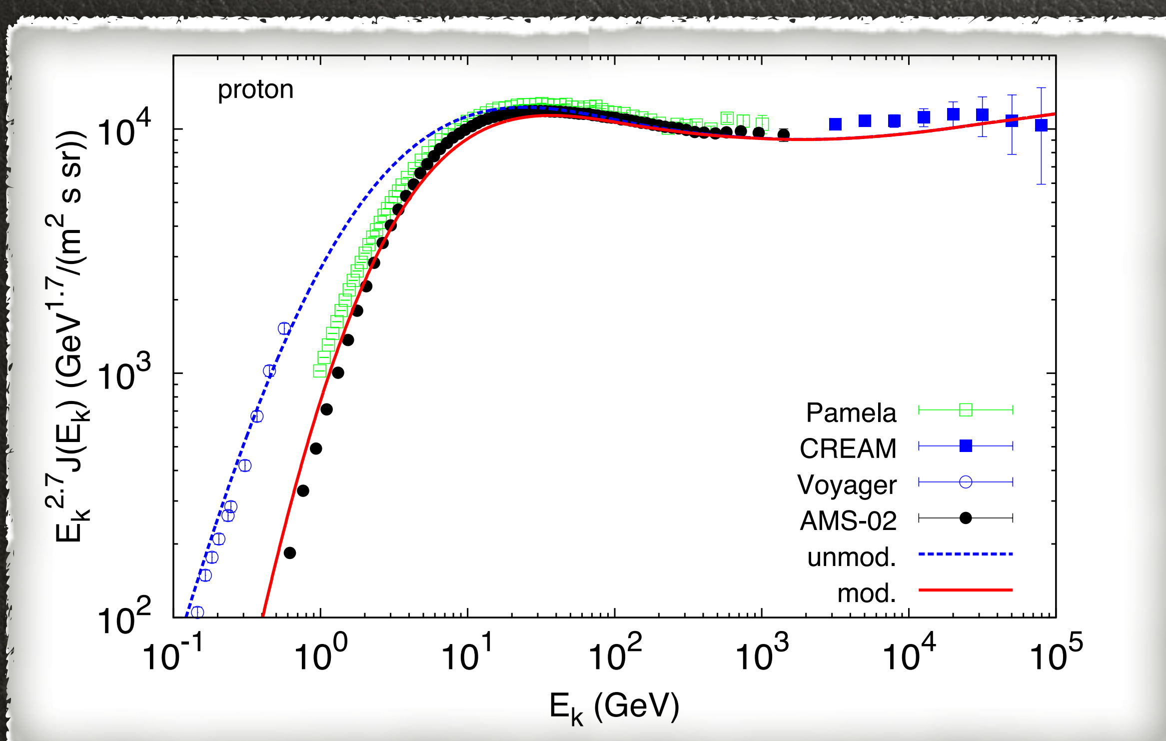
NON LINEAR GALACTIC TRANSPORT

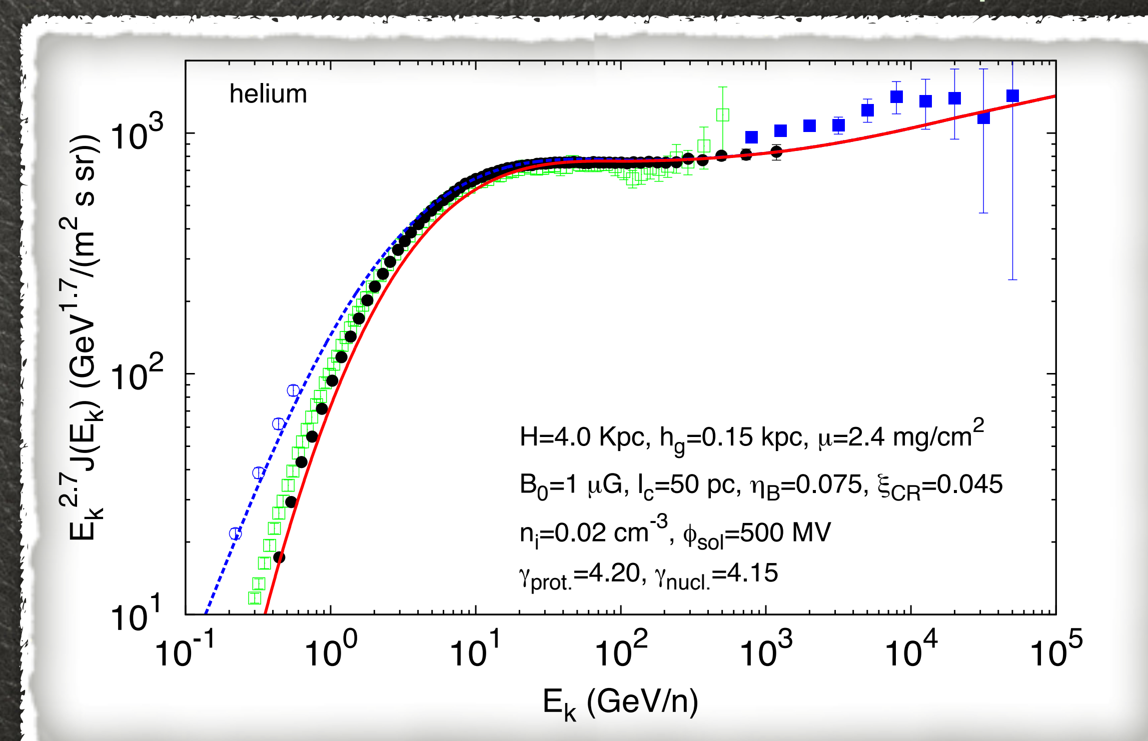
I. SELF-GENERATED WAVES VS PRE-EXISTING

Waves can cascade down from large scales (e.g. SNe) and be injected on resonant scales through streaming instability

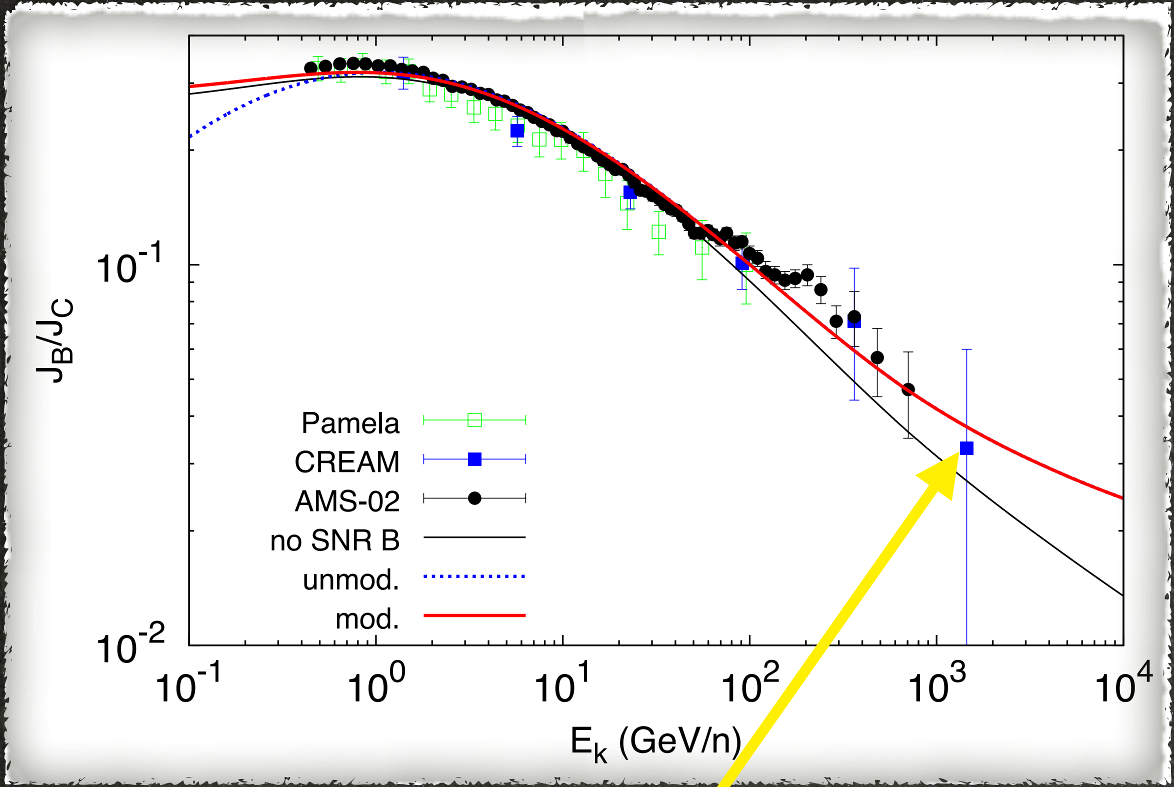
The combination of the two phenomena leads to different energy scalings of D(p) and hence of anisotropy [*PB, Amato & Serpico 2012, Aloisio & PB 2014, Aloisio, PB & Serpico 2015*] — This phenomenon reflects in spectral breaks

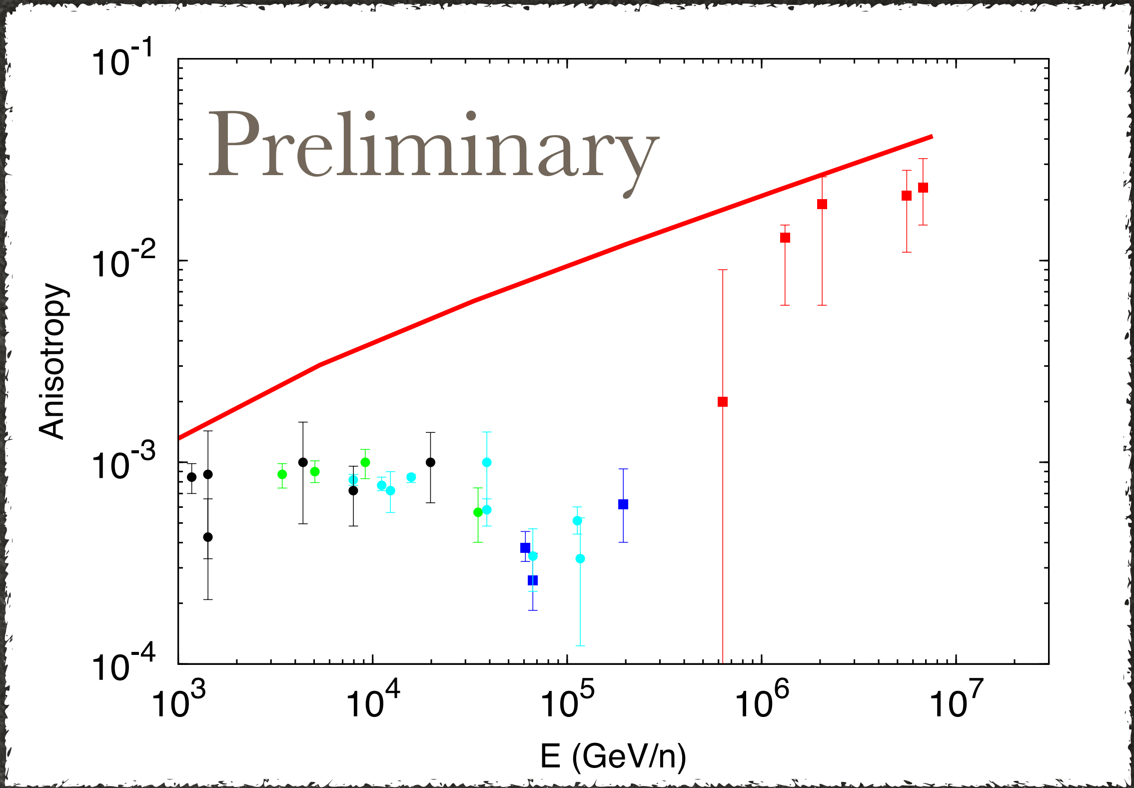
Aloisio, PB & Serpico 2015





B/C RATIO AND ANISOTROPY





Aloisio, PB & Serpico 2015

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

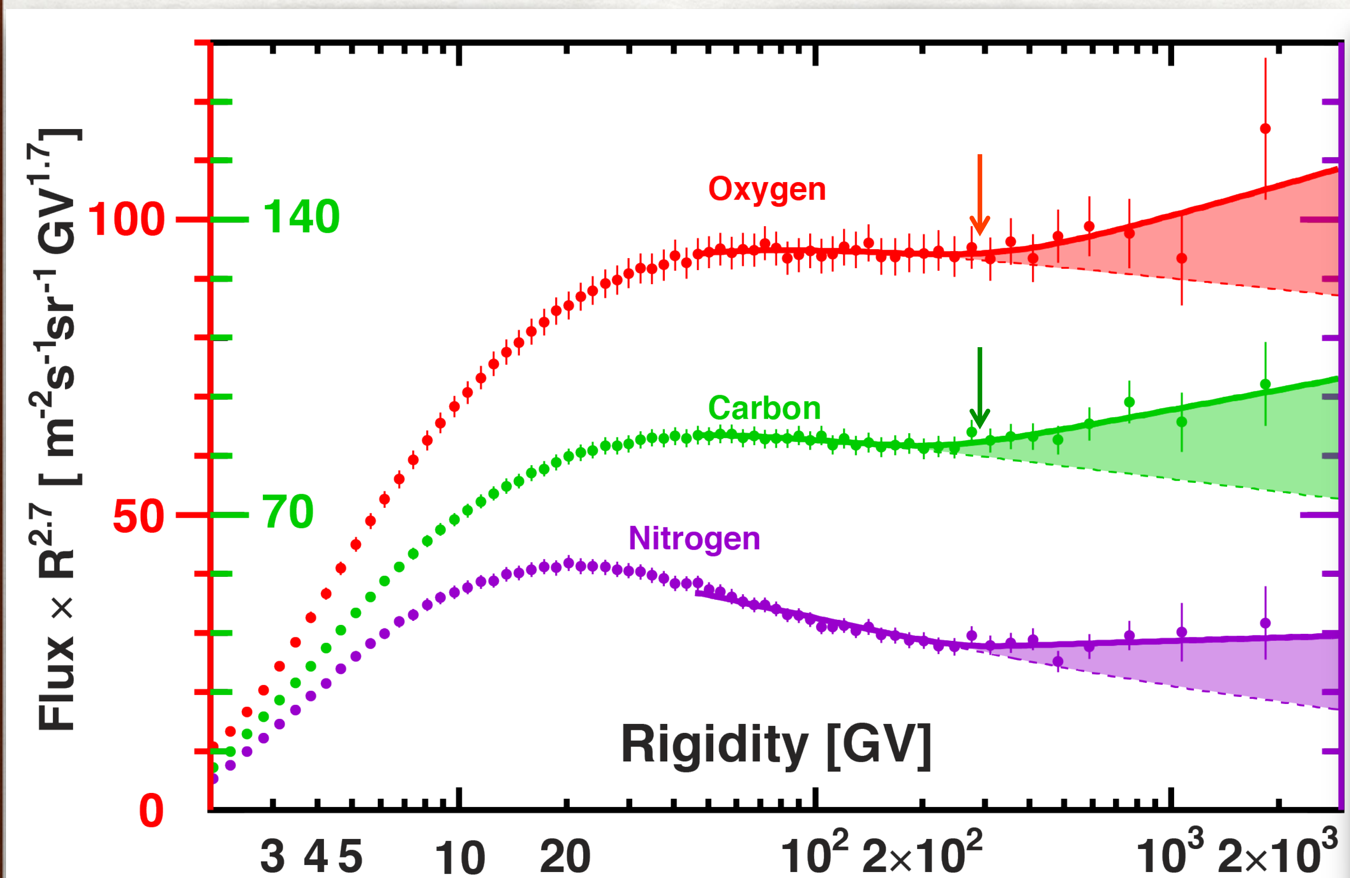
The hardening of the spectra also corresponds to a flattening of the anisotropy at high energy

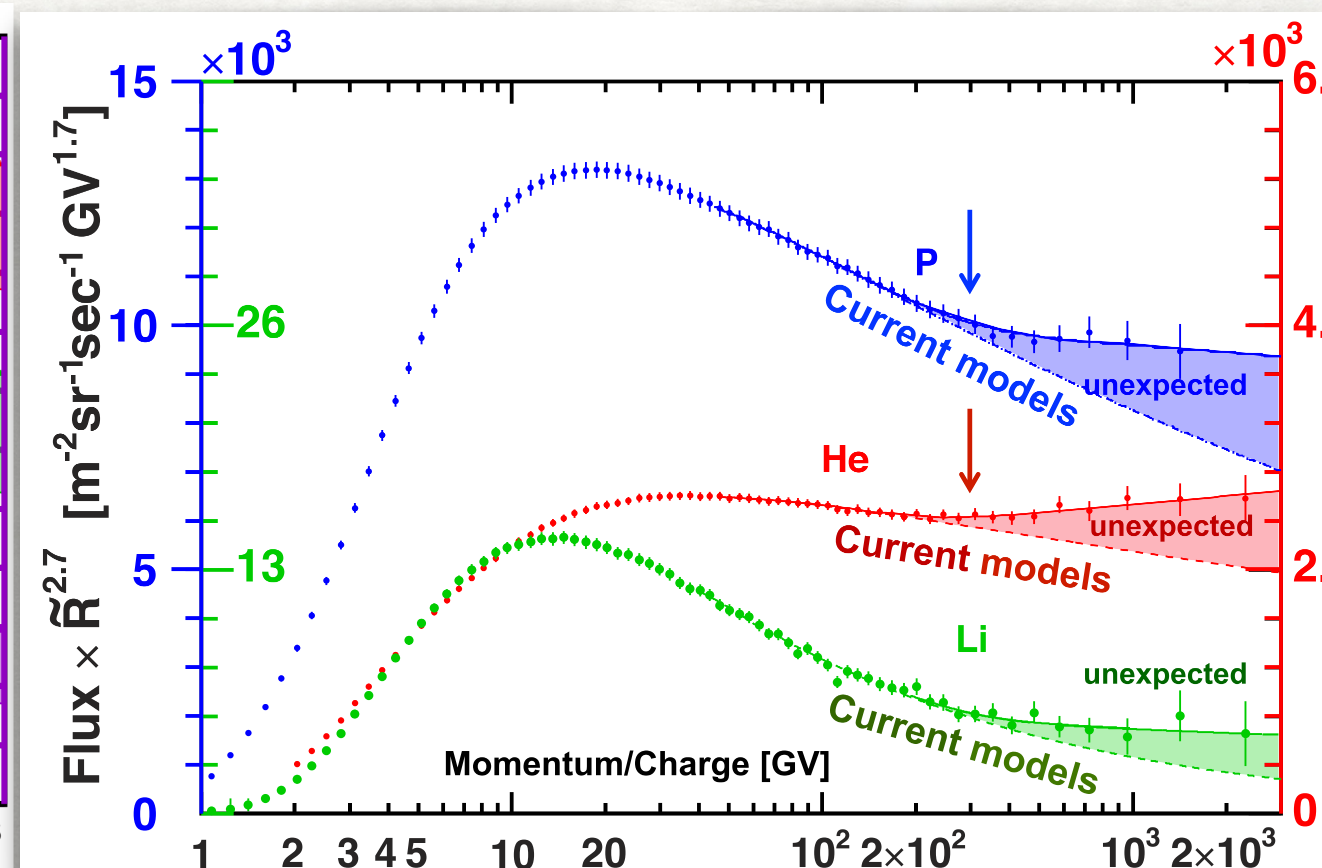
No discrete sources were introduced here, hence only the regular trend of the anisotropy is shown, the wild fluctuations may be responsible for dips and bumps

A GENERAL TREND?

A change of slope around 300 GV seems to be visible in measurements of the fluxes of both primary and secondary nuclei

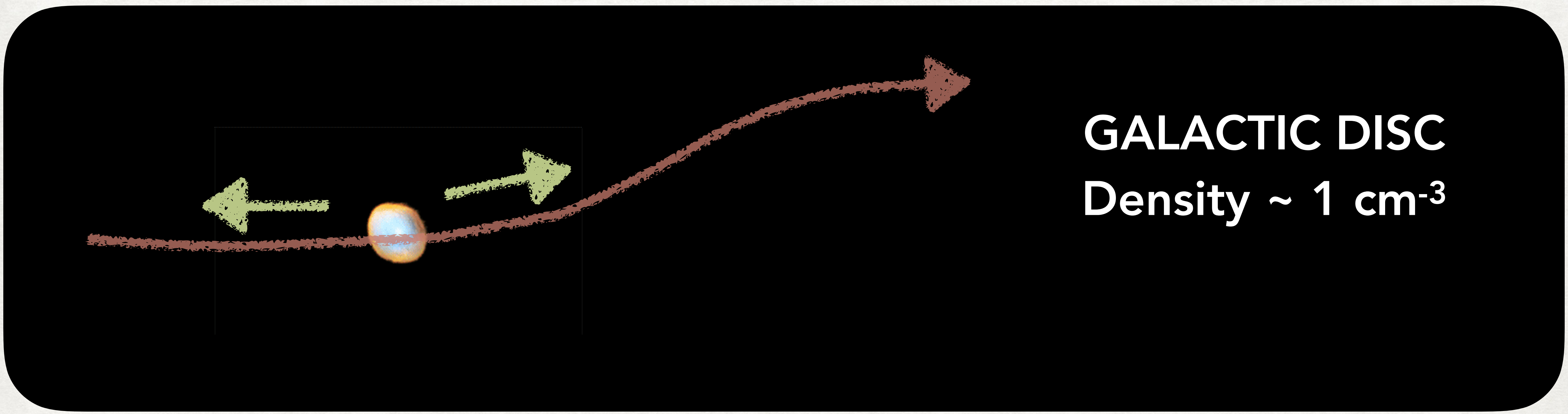
Whether this happens because of a break in the injection spectra or in the diffusion coefficient could be understood from quantitative assessment of the slopes below and above the break for primaries and secondaries





GRAMMAGE ACCUMULATED NEAR THE SOURCES

NEAR THE SOURCES THE DENSITY OF CR AND THE GRADIENTS ARE LARGE ENOUGH THAT INSTABILITIES ARE EXCITED AND MAY CONFINE CR CLOSE TO THE SOURCES FOR LONG TIMES



ACCOUNTING FOR THIS PROBLEM REQUIRES SOLVING A TIME DEPENDENT NON-LINEAR DIFFUSION PROBLEM

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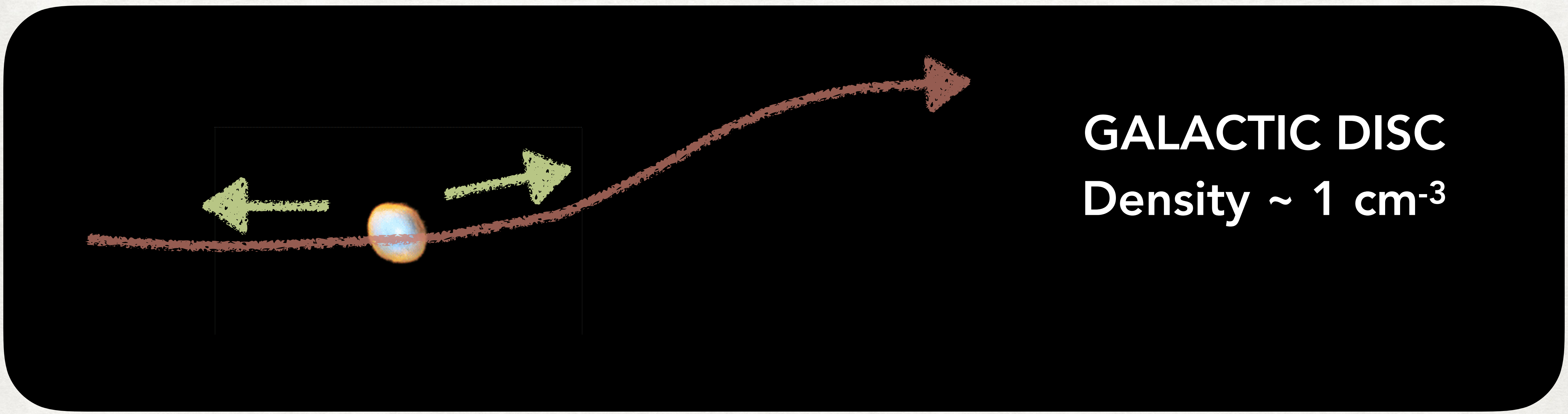

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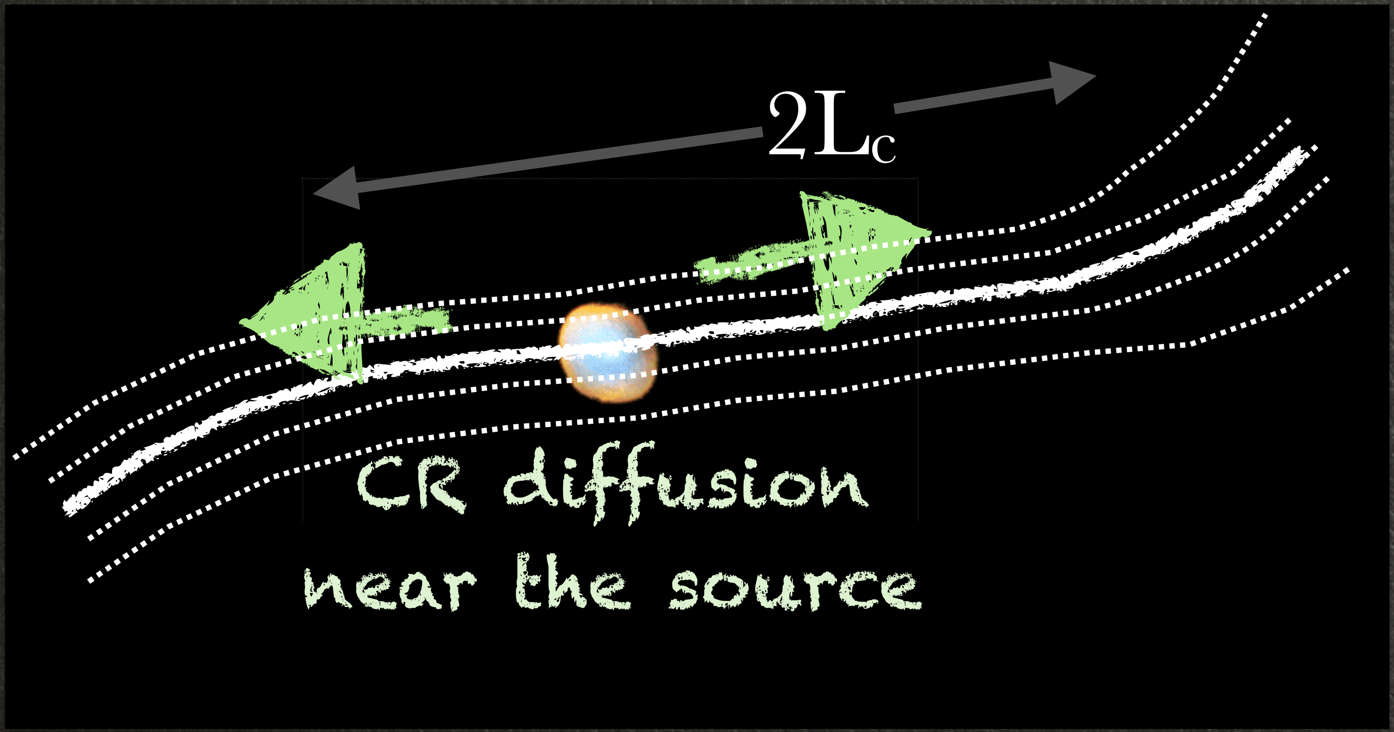
NEAR SOURCE TRANSPORT

The gradients in the particle distribution around a source are very large and can lead to excitation of fast streaming instability



In the absence of non-linear effects the CR density inside Lc remain > than the Galactic average for a time

$$t_s \sim 2 \times 10^4 E_{GeV}^{-1/3} \; yr$$

After that, propagation becomes 3D and the density drops rapidly

In the presence of non-linear effects waves are excited and damped:

$$\Gamma_{\rm CR}(k) = \frac{16\pi^2}{3}\frac{v_{\rm A}}{\mathcal{F}B_0^2}\left[p^4 v(p)\frac{\partial f}{\partial z}\right]_{p=qB_0/kc} \equiv \Gamma_{NL} = (2c_K)^{-3/2} k v_A \mathcal{F}^{1/2}$$

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

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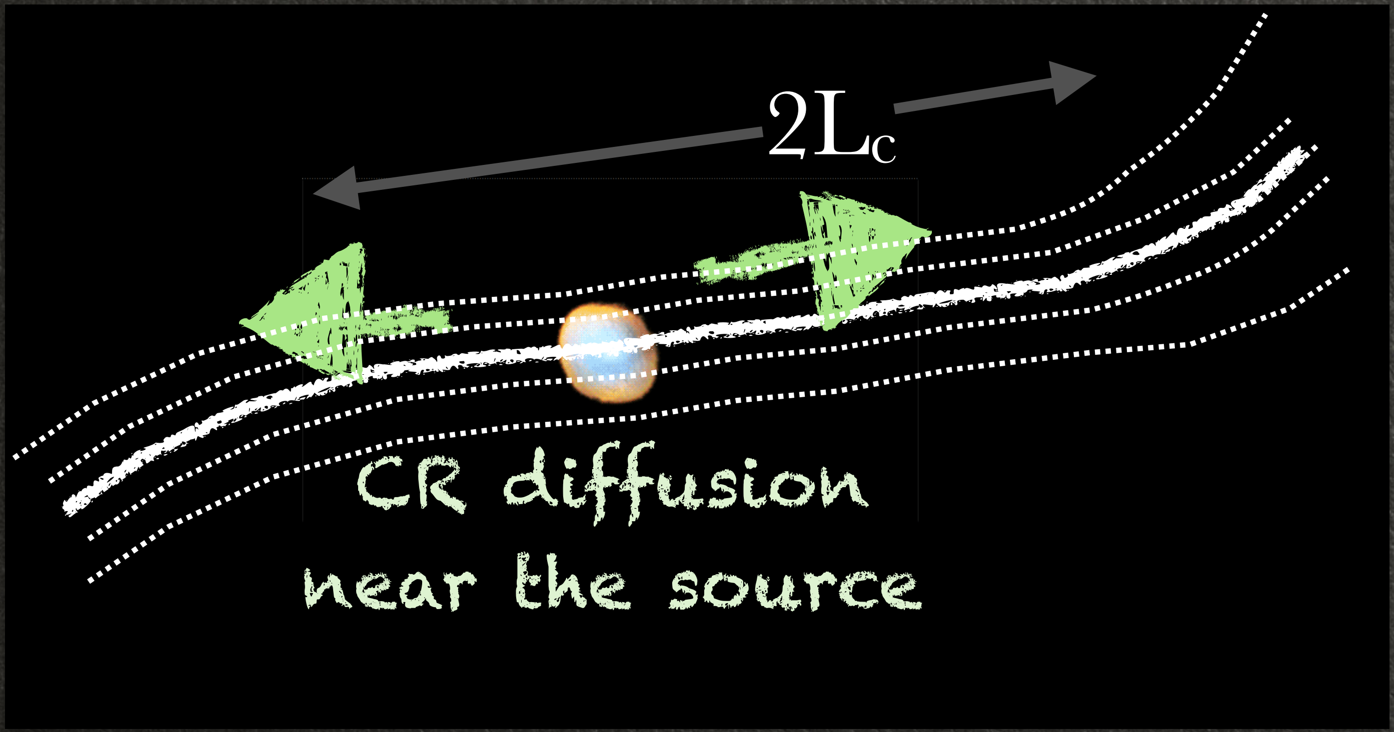

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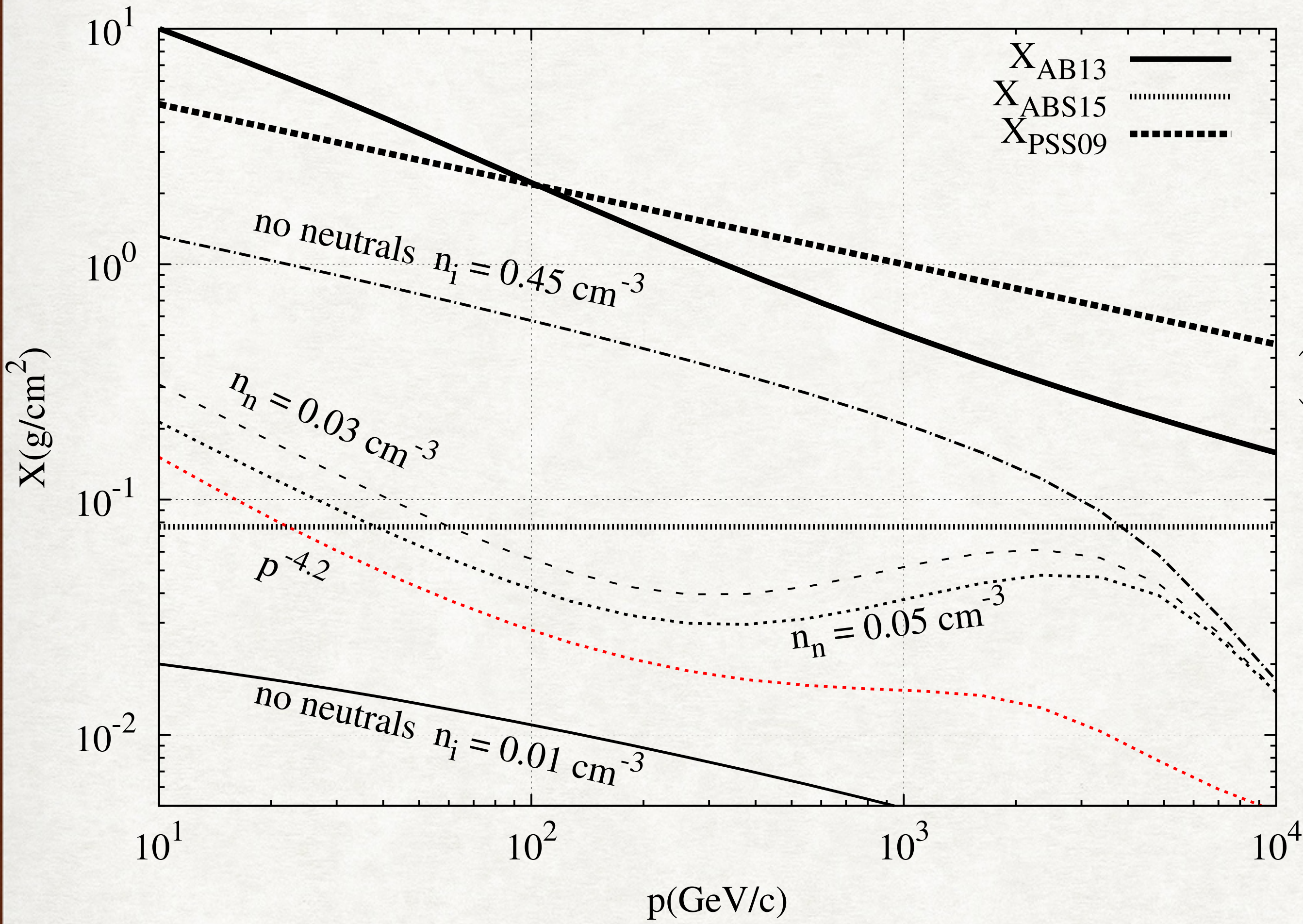
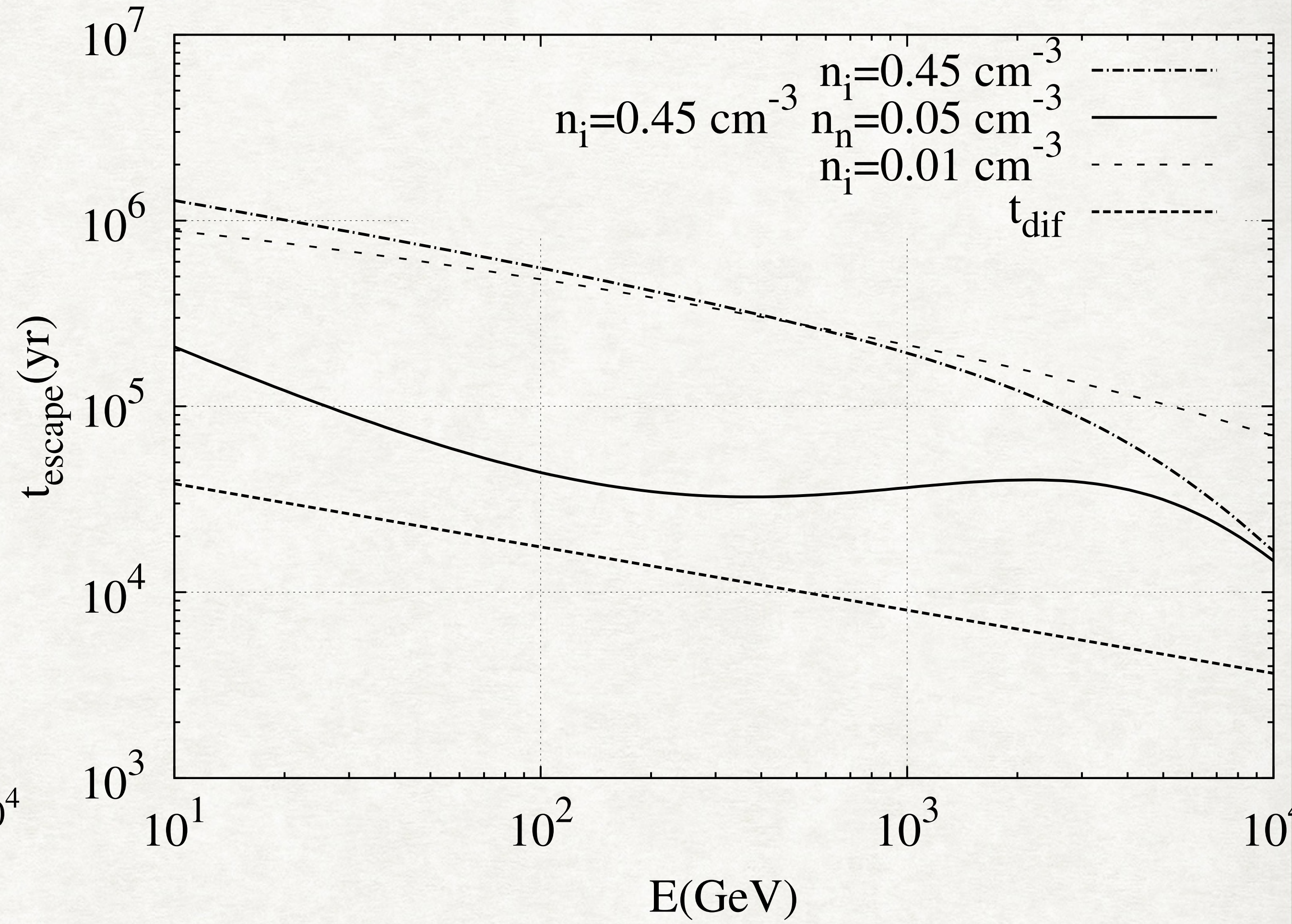
GRAMMAGE ACCUMULATED NEAR THE SOURCES



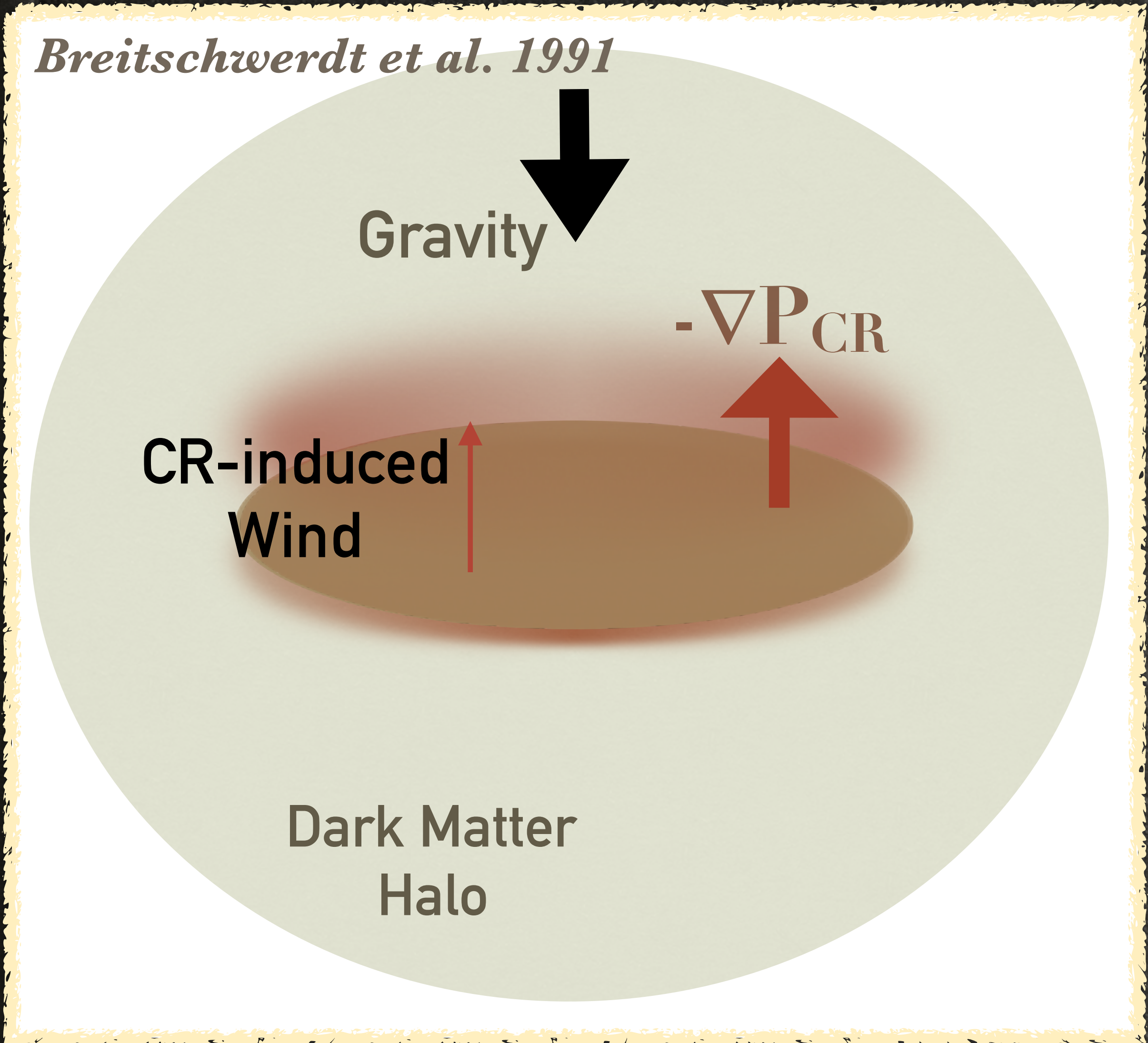


D'Angelo, PB & Amato 2017

THE NON LINEAR EFFECTS INDUCED BY CR CAN LEAD TO AN ENHANCED CONFINEMENT TIME CLOSE TO THE SOURCE IF MEDIUM IONIZED

IF NEUTRALS PRESENT, ION-NEUTRAL DAMPING LIMITS THIS PHENOMENON

Cosmic Rays vs Gravity: Cosmic Ray Induced Galactic Winds



The force exerted by CR may win 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

Cosmic Rays vs Gravity: CR driven winds

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

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

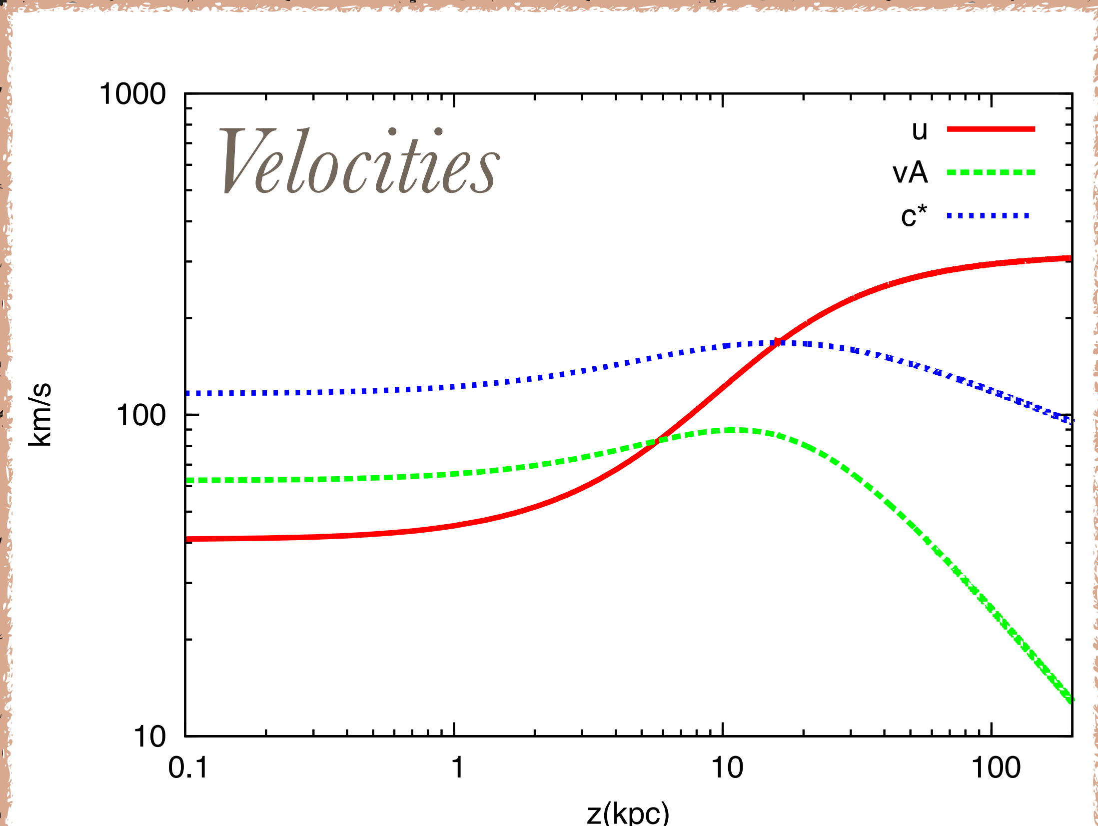
Ptuskin et al. 1997

No effective halo size H

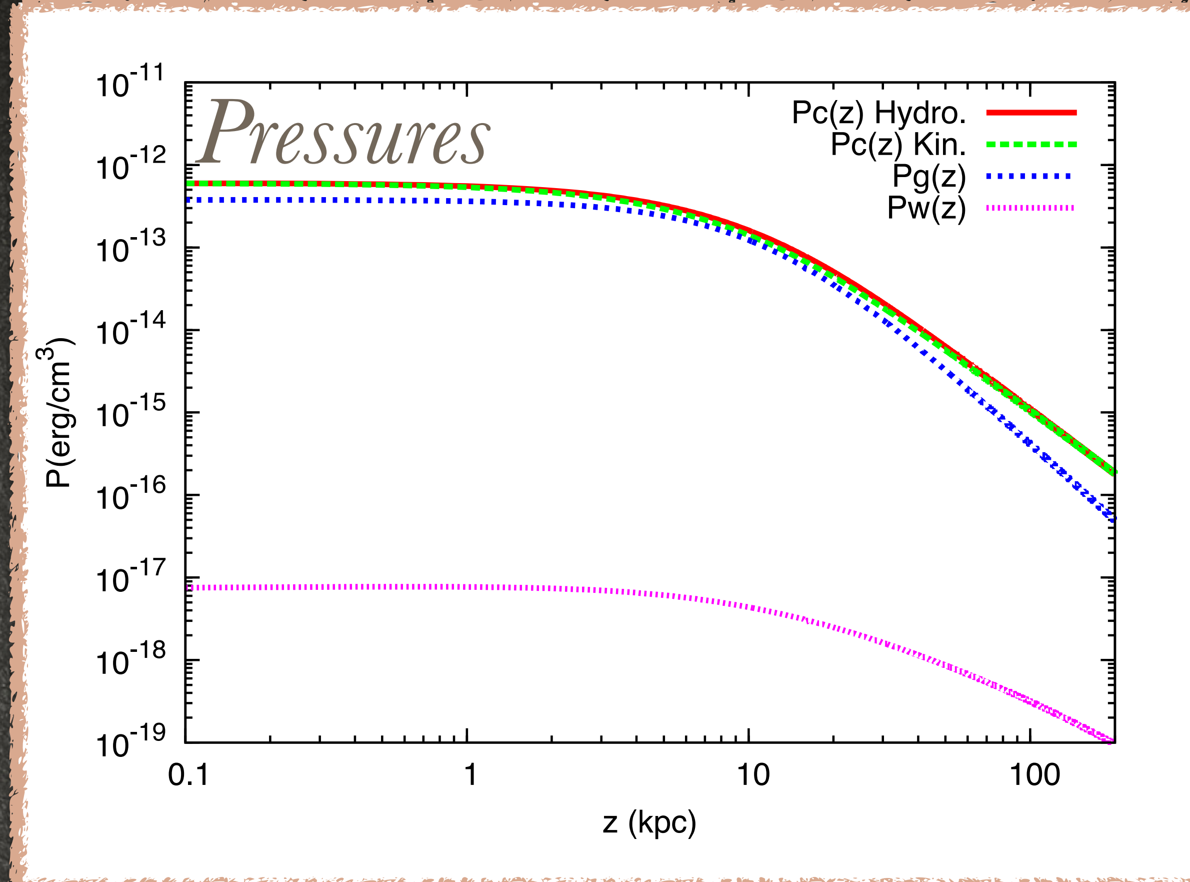
$$f_0(p) = \frac{Q(p)}{2A_{disc}} \frac{H}{D(p)} \sim E^{-\gamma-\delta} \qquad f_0(p) = \frac{Q(p)}{2A_{disc}} \frac{z_*(p)}{D(p)} \sim E^{-\gamma-\delta/2}$$

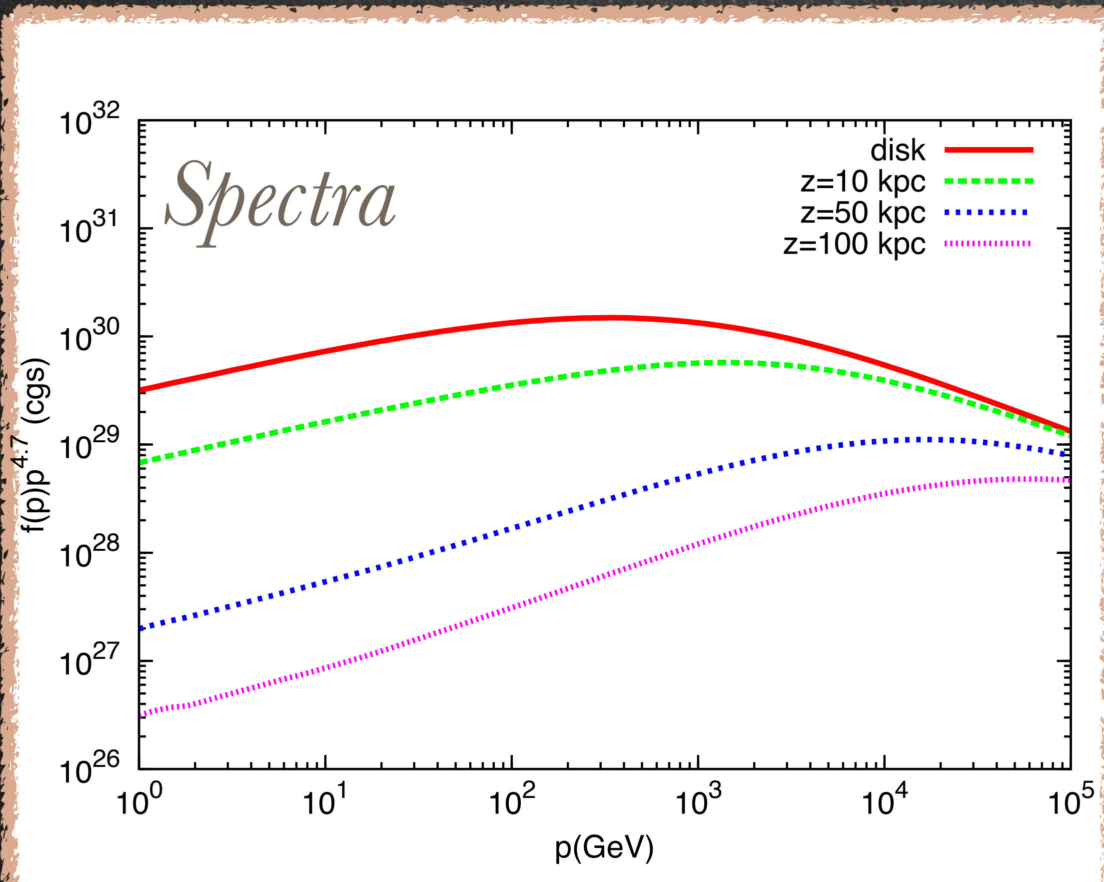
STANDARD CASE — **CR-INDUCED WIND WITH SELF-GENERATION**

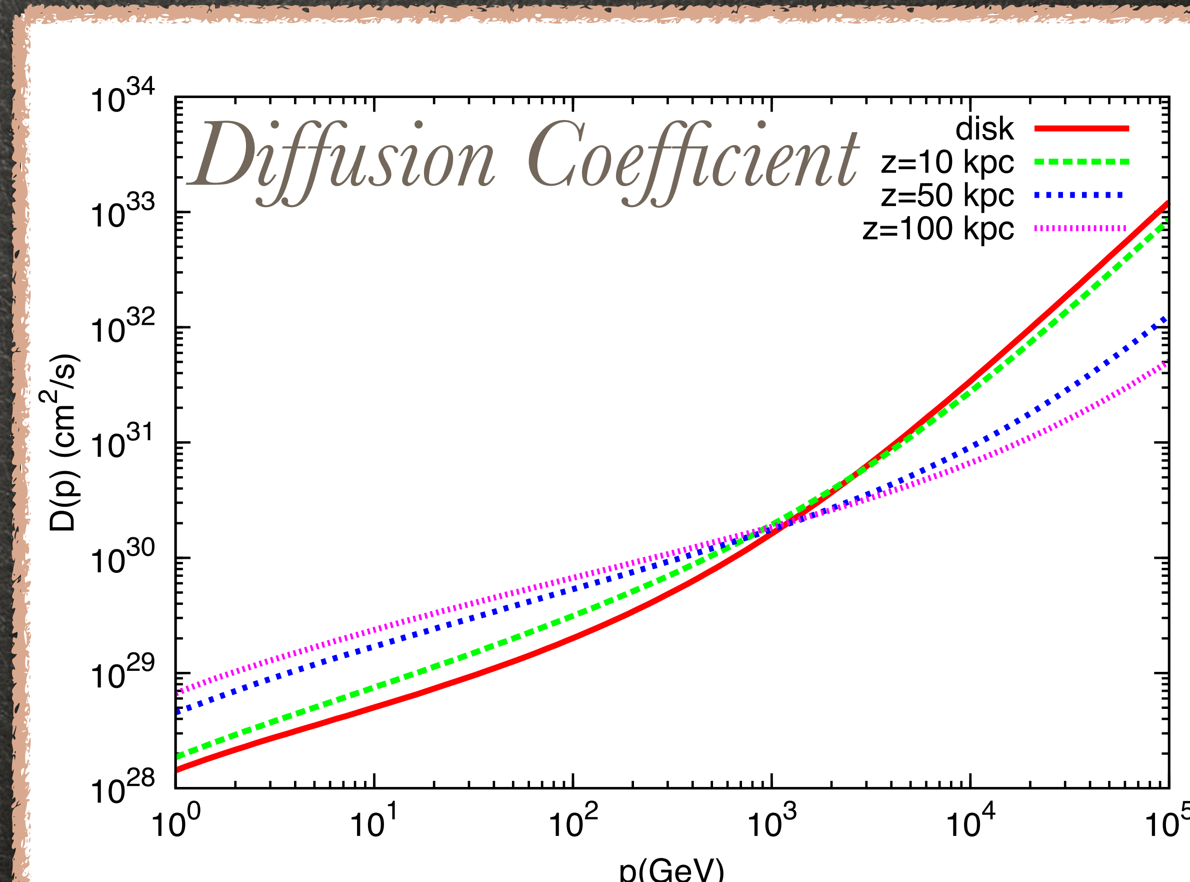
At high energy, the critical scale becomes larger than the location where the geometry to he wind becomes spherical, and a steepening of the spectrum may be expected



Recchia, PB & Morlino 2017

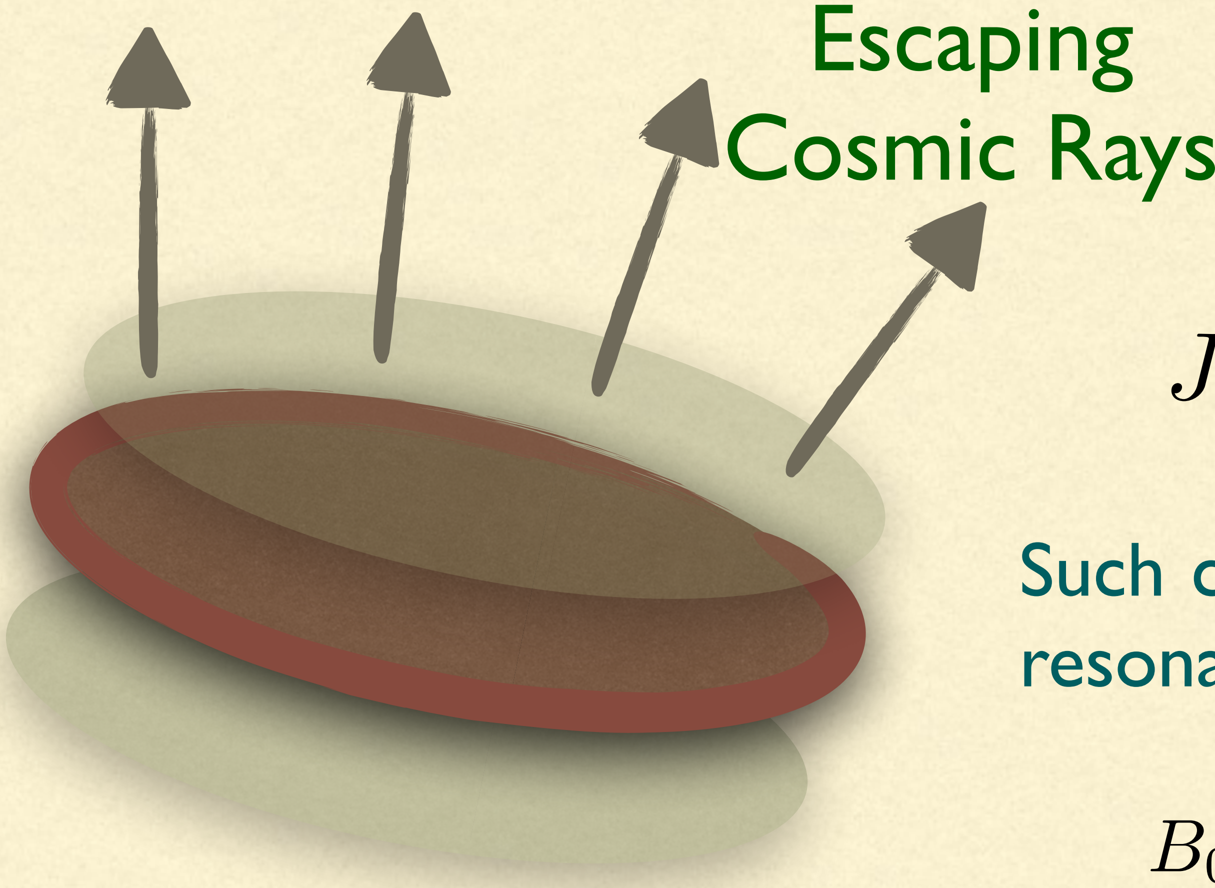






ESCAPING THE GALAXY

PB&Amato 2019



As discussed above, the current of escaping CRs is very well known

$$J_{CR}(p) = eD\frac{\partial f}{\partial z}|_{z=H} = \frac{eQ_0(p)}{2\pi R_d^2}$$

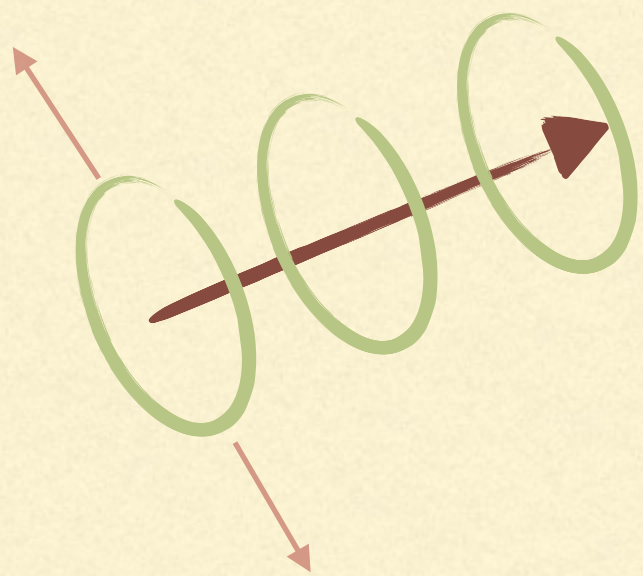
Such current in the typical IGM excites a non-resonant Bell-like instability provided:

$$B_0 \le B_{sat} \approx 2.4 \times 10^{-8} L_{41}^{1/2} R_{10}^{-1}\ \mathrm{G}$$

At a wavenumber $k_{max} = \frac{4\pi}{cB_0} J_{CR}$

and with a growth rate: $\gamma_{max} = k_{max} v_A \approx 0.5\ \mathrm{yr}^{-1}\ \delta_G^{-1/2} E_{\mathrm{GeV}}^{-1} L_{41} R_{10}^{-2}$

THE EASY WAY TO SATURATION



The current exerts a force of the background plasma

$$\rho \frac{dv}{dt} \sim \frac{1}{c} J_{CR} \delta B$$

which translates into a plasma displacement:

$$\Delta x \sim \frac{J_{CR}}{c\rho} \frac{\delta B(0)}{\gamma_{max}^2} exp(\gamma_{max} t)$$

which stretches the magnetic field line by the same amount…

The saturation takes place when the displacement equals the Larmor radius of the particles in the field **δ**B

$$\delta B \approx B_{\rm sat} \approx \sqrt{\frac{2 L_{CR}}{c\ R_d^2 \Lambda}} \approx 2.4 \times 10^{-8} L_{41}^{1/2} R_{10}^{-1}\ \mathrm{G}$$

WHAT'S GOING ON?

We started from the assumption that CR escape freely and we got to the conclusion that perturbations are generated

I remind you that the escape spectrum is ~Q(p)~p^{-4} hence the spectrum of perturbations is scale invariant

One would be tempted to assume that CR would diffuse, but after a few γ_{max}^{-1} the pressure gradient built up because of scattering becomes sufficient to set the background plasma in motion with the speed

$$v_D \approx \frac{\delta B}{(4\pi\Omega_b\rho_{cr}\delta_G)^{1/2}} \sim 10 - 100 \text{ km/s}$$

local gas overdensity

PICTURE

When escaping CR reach a region where the field drops below ~10^{-8} G, they excite a non-resonant instability that sets the plasma in motion

Hence, their density is set by advection

$$n_{CR}(E) = \frac{\phi_{CR}}{\tilde{v}_A}$$

Instead of escaping at c they move at speed v_D so that their density is much higher around the Galaxy than in the case of free streaming

ASTROPHYSICAL NEUTRINOS

COSMIC RAYS THAT ATTEMPTED ESCAPE FROM THE GALAXY ARE ACTUALLY TRAPPED IN A CIRCUMGALACTIC REGION, WHERE THE GAS DENSITY IS ABOUT ~200 $\Omega_b \rho_{cr}$

NEUTRINOS ARE PRODUCED THROUGH INELASTIC HADRONIC COLLISIONS

$$F_\nu(E_\nu)E_\nu^2 \approx \frac{L_{CR}}{2\pi R_d^2 \Lambda \tilde{v}_A} \frac{E_\nu^2}{E^2} \frac{dE}{dE_\nu} \frac{\delta_G \Omega_b \rho_{cr}}{m_p} \frac{c\sigma_{pp} R_d}{2\pi}$$