# NON LINEAR COSMIC RAY TRANSPORT

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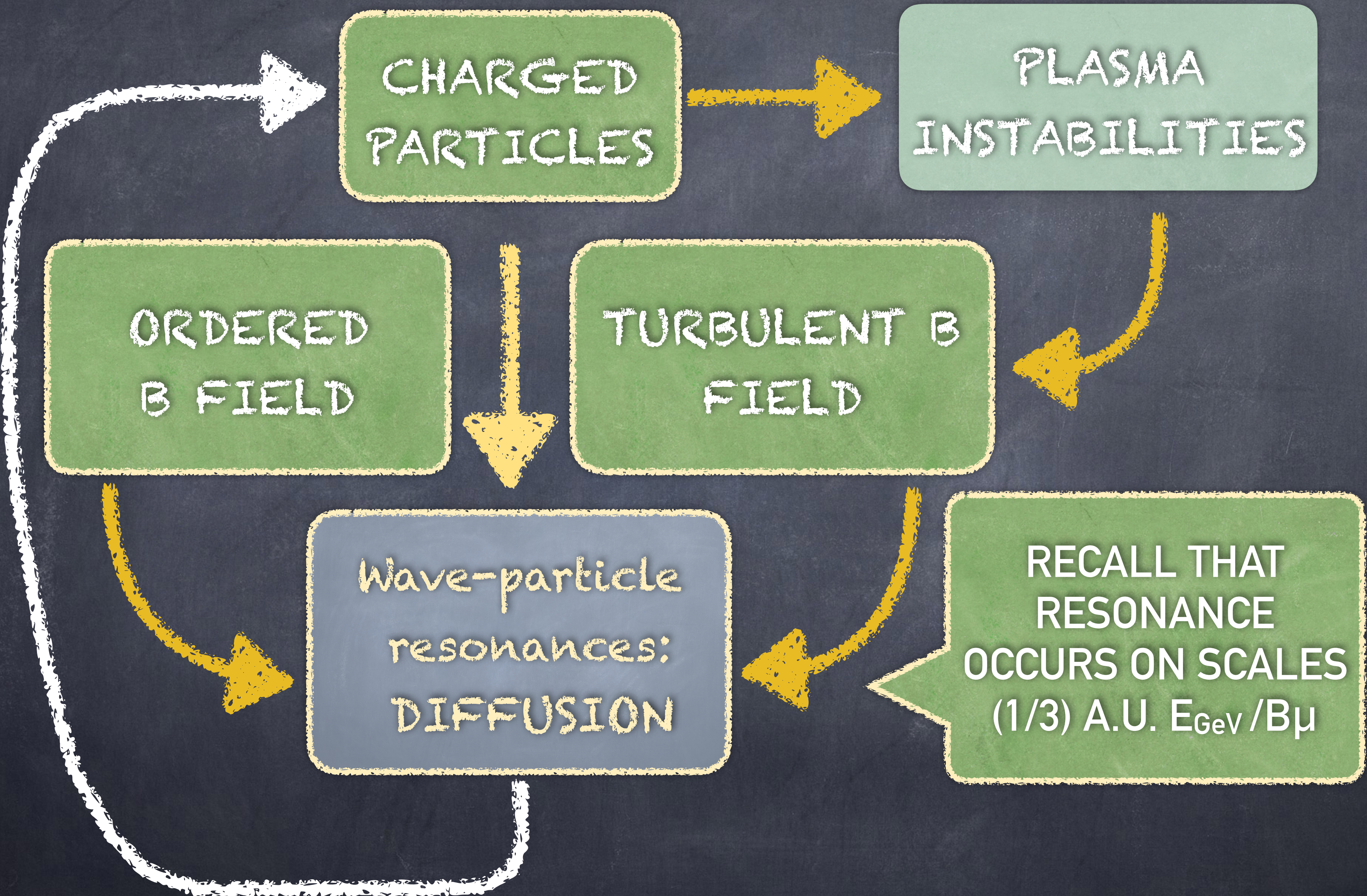
# WHY GOING NON LINEAR?

Non linear effects are known to be important in particle acceleration (strong currents, large anisotropies, fast instabilities)

Here we discuss instances of non linearities in describing transport of CRs around sources and on global scales

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


CHARGED PARTICLES
PLASMA INSTABILITIES
ORDERED B FIELD
TURBULENT B FIELD
Wave-particle resonances: DIFFUSION
RECALL THAT RESONANCE OCCURS ON SCALES (1/3) A.U. $E_{GeV}$ /Bμ

# 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

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

# GROWTH OF THE NON RESONANT MODE

This regime is realised in the regime of strong CR current:

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

For CR streaming at the speed of light this condition coincides with $U_{CR} \gg U_B$

IMPORTANT: the instability is non resonant, hence the total CR current counts, not only the resonant particles

The instability grows fast on scales much smaller than the larmor radius of the particles dominating the current

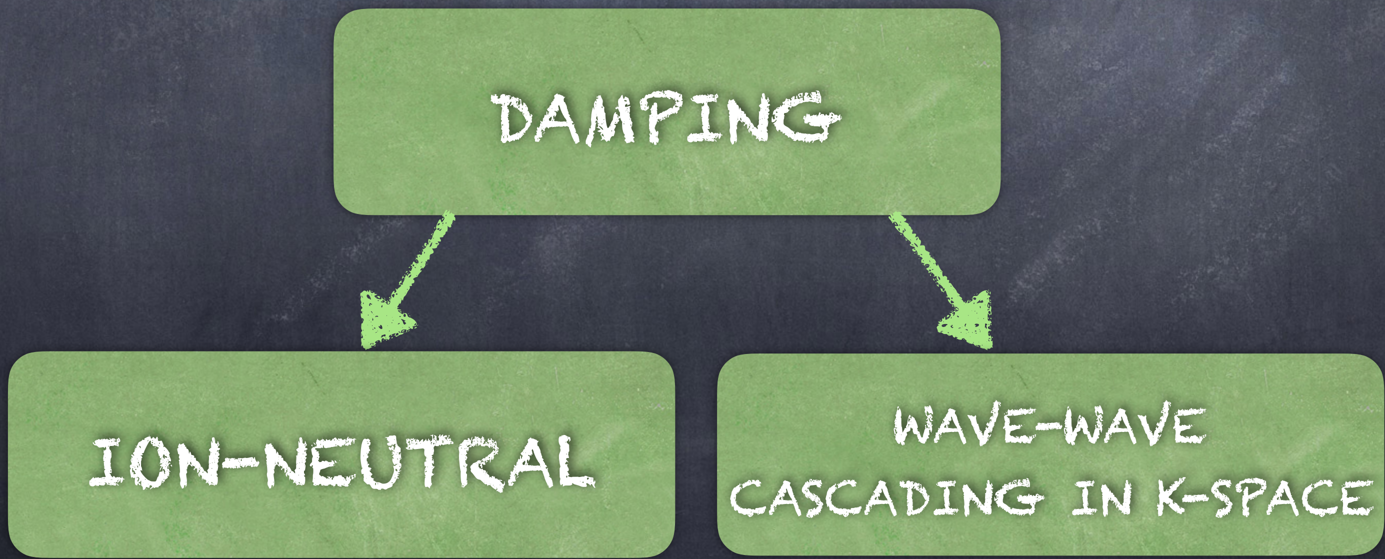
The excited modes are not Alfven waves (quasi-purely growing)

# SATURATION OF STREAMING INSTABILITY

Saturation may occur because the CR CURRENT IS DISRUPTED or because WAVES ARE DAMPED

As a rule of thumb damping dominates the saturation of the resonant modes

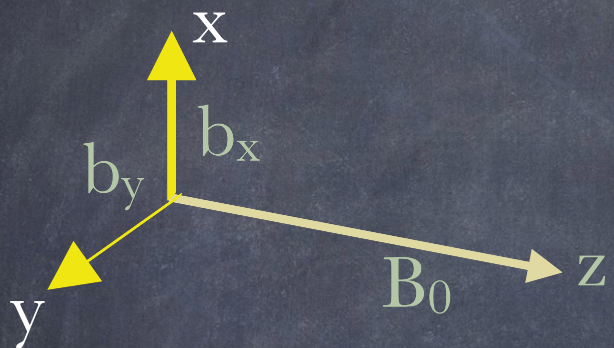
Current disruption stops the growth of the non-resonant modes



# GROWTH vs SCATTERING

**GROWTH CAN BE NON-RESONANT BUT SCATTERING STILL REQUIRES RESONANCE**

**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

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

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

Resonance

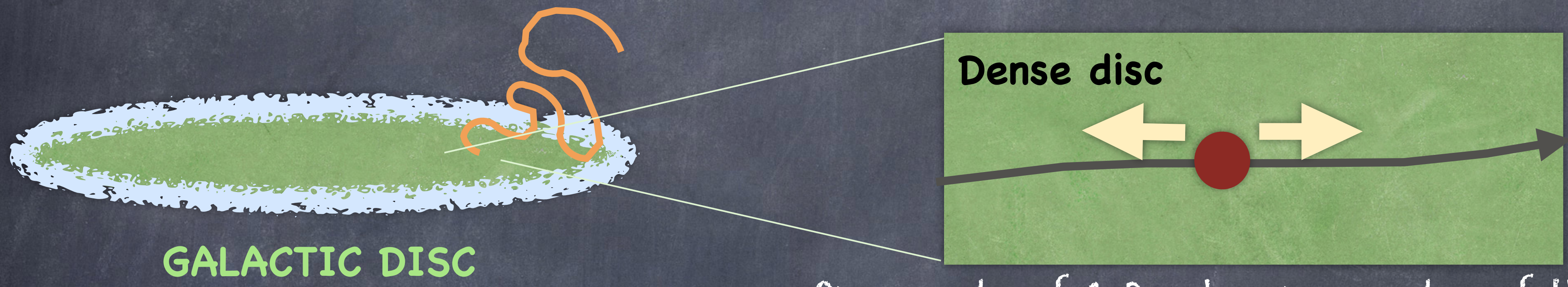
Diffusion

# NON LINEAR COSMIC RAY TRANSPORT:

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

D’Angelo, PB & Amato, PRD 2016

# 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

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

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

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?

# ROLE OF CASCADING (NLLD)

IF THE ISM IS COMPLETELY IONIZED THEN THIS IS THE DOMINANT DAMPING PROCESS FOR ALFVEN WAVES

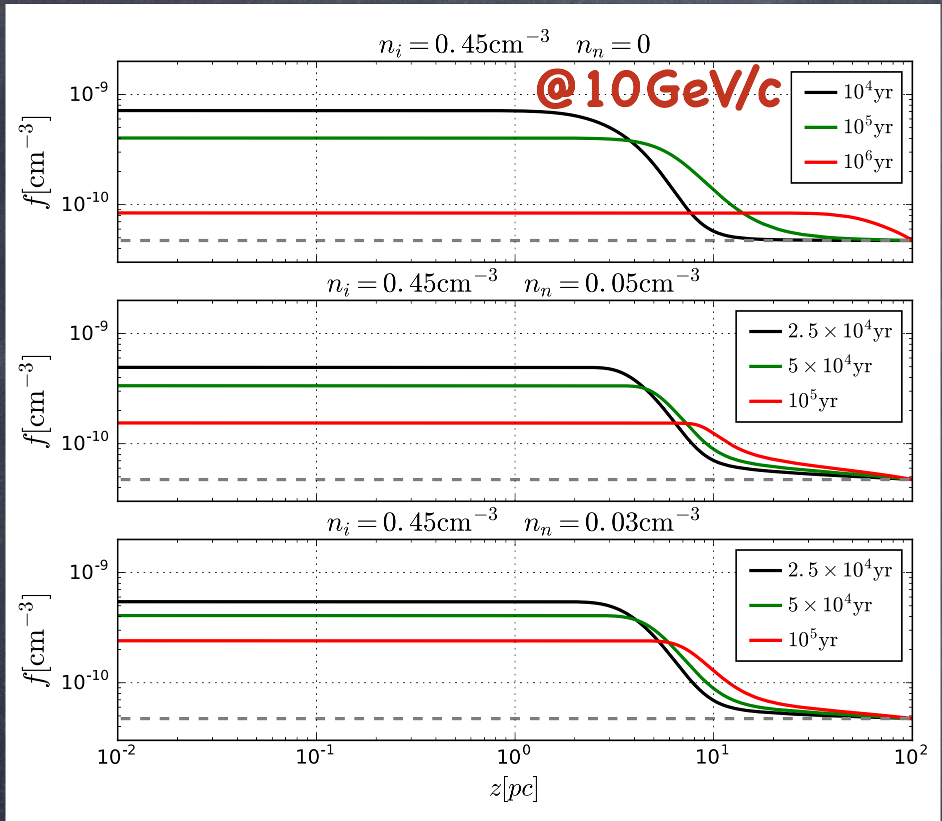
IT CAN BE MODELLED AS DIFFUSION IN K SPACE. FOR KOLMOGOROV CASCADE:

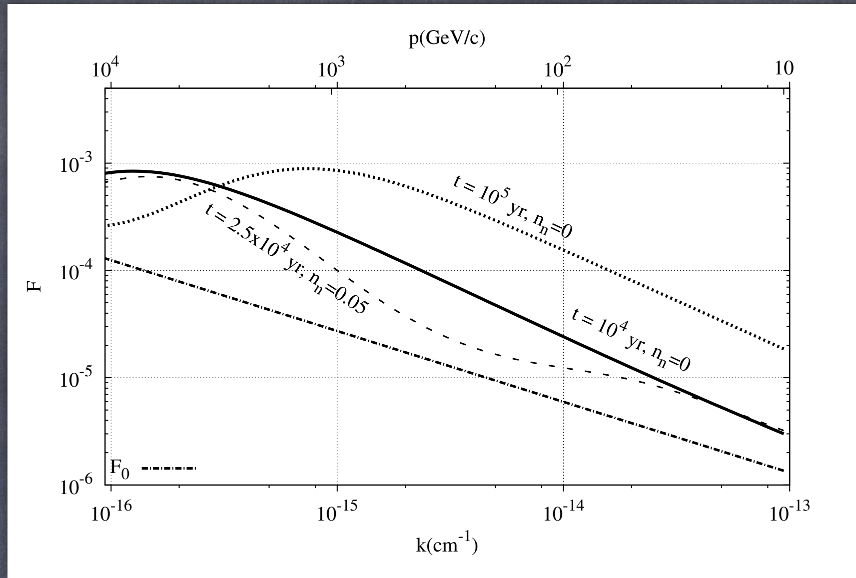
$$D_{kk} = C_K v_A k^{7/2} \left(\frac{\mathcal{F}}{k}\right)^{1/2} \qquad C_K \sim 5 \times 10^{-2}$$

$$\Gamma_{NL} \approx \frac{D_{kk}}{k^2} \propto k v_A \mathcal{F}^{1/2}$$

If injection is at a single scale, left to itself, this process leads to formation of a Kolmogorov spectrum

# RESULTS



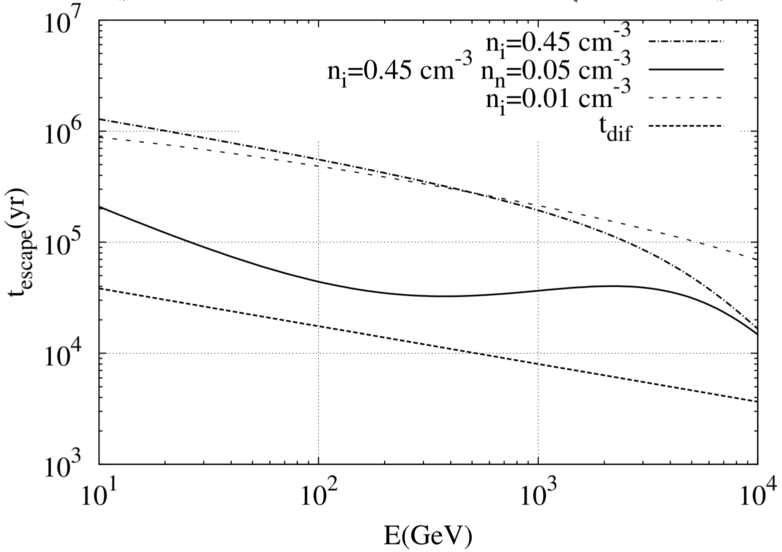

D'ANGELO + 2016

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

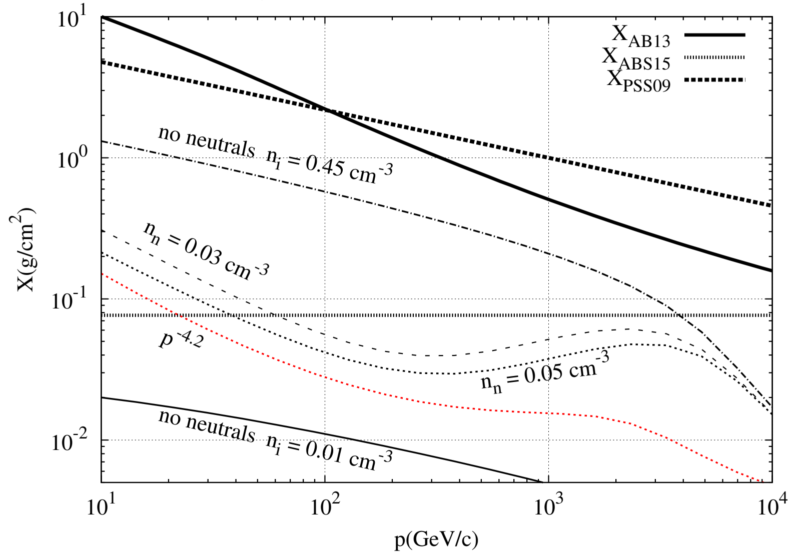
[qualitatively similar results obtained by Malkov et al. (2013) with IND and by Ptuskin et al. (2007) in case of ionized target. More recently, calculations by Nava et al. (2016).]

# 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

FOR A DISCUSSION OF THE ROLE OF THIS GRAMMAGE FOR DIFFUSE GAMMA RAY EMISSION SEE TALK BY G. Morlino

# NON LINEAR COSMIC RAY TRANSPORT:

# 2) CR INDUCED INSTABILITIES ON GALACTIC SCALES AND IMPLICATIONS FOR SPECTRUM AND RADIAL GRADIENT

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


CR Gradient
directed towards
outer halo

Transport eq for all nuclei

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

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

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

Power law in p

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

THE EQUATION FOR THE WAVES IS:

Damping as diffusion in k-space

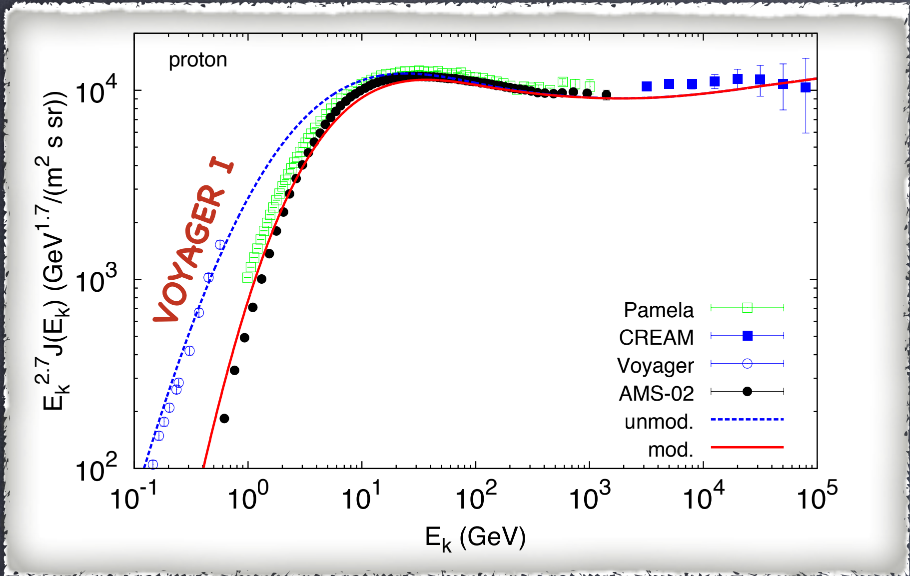
$$\frac{\partial}{\partial k}\left[D_{kk}\frac{\partial W}{\partial k}\right]+\Gamma_{\rm CR}W=q_W(k)$$

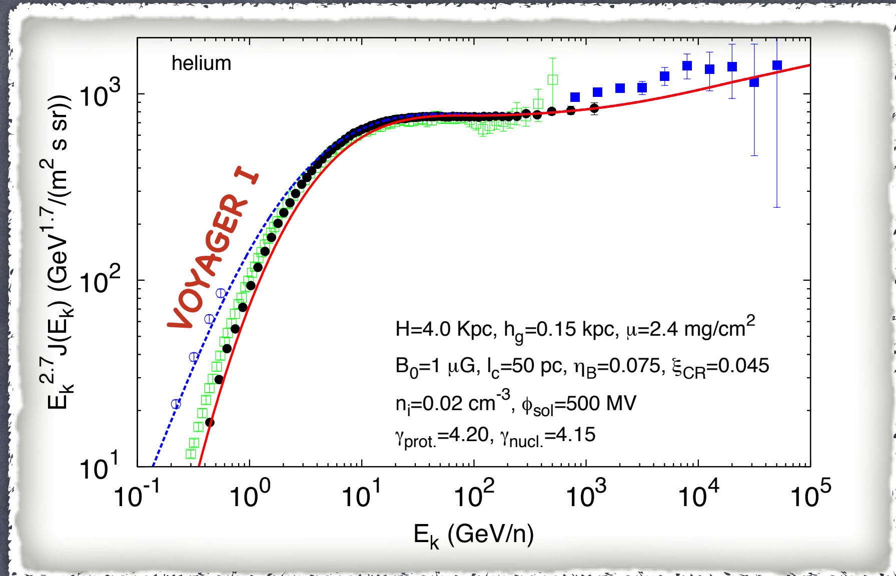
$$\Gamma_{CR}(k)=\frac{16\pi^2}{3}\frac{v_A}{B_0^2\mathcal{F}(k)}\sum_\alpha\left[p^4v_\alpha(p)\frac{\partial f_\alpha}{\partial z}\right]_{p=p_{res,\alpha}(k)}$$

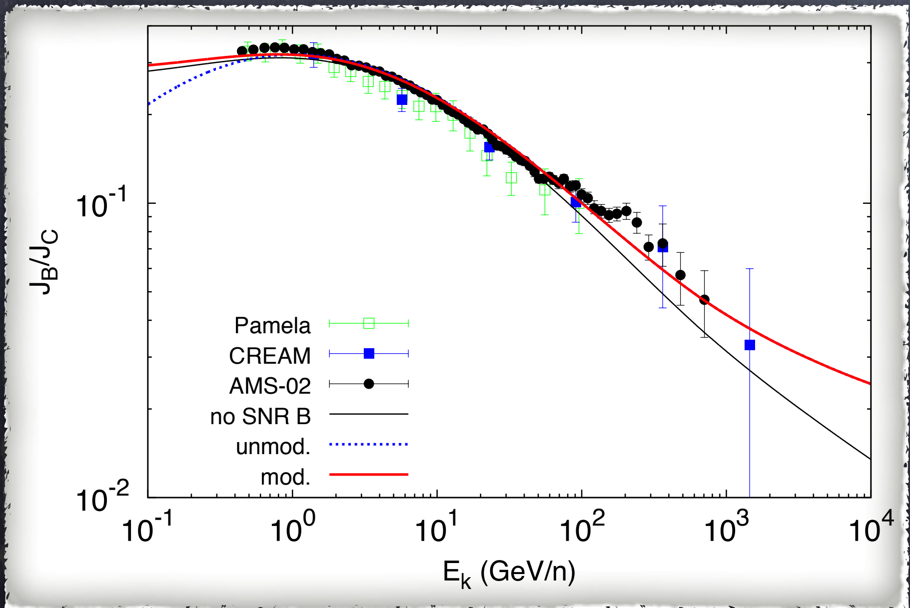
SUM OVER ALL NUCLEI OF THE RIGHT MOMENTUM TO GENERATE A WAVE WITH GIVEN k

# 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?

AMS-02 B/C shows an excess at E>100GeV, compatible with the grammage inside sources:

$$X_{SNR} \approx 1.4 r_s m_p n_{ISM} c T_{SNR} \approx 0.17\ \mathrm{g\,cm^{-2}} \frac{n_{ISM}}{\mathrm{cm^{-3}}} \frac{T_{SNR}}{2\times10^4\mathrm{yr}}$$

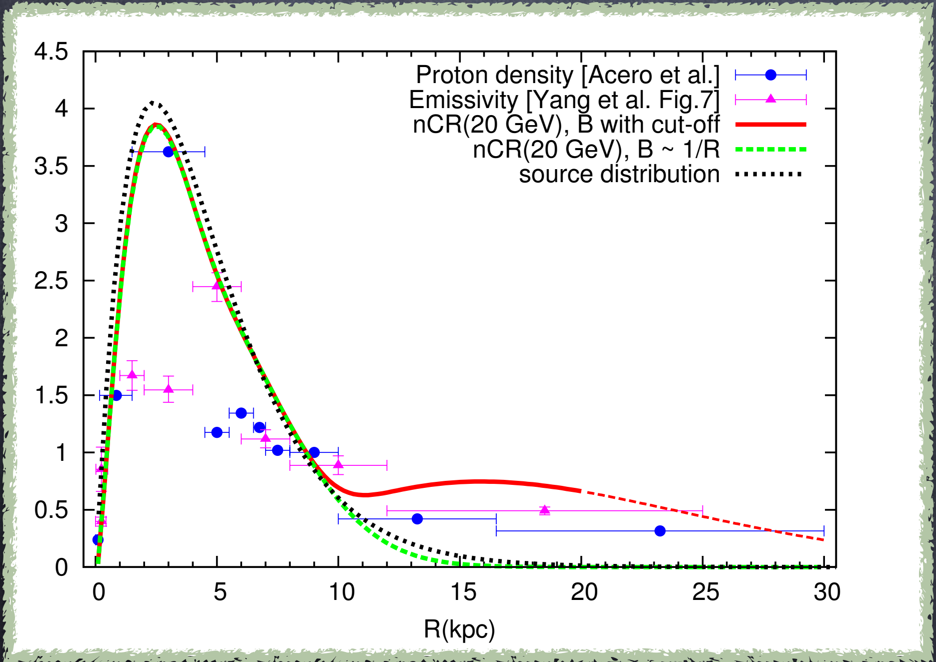
# The CR Gradient

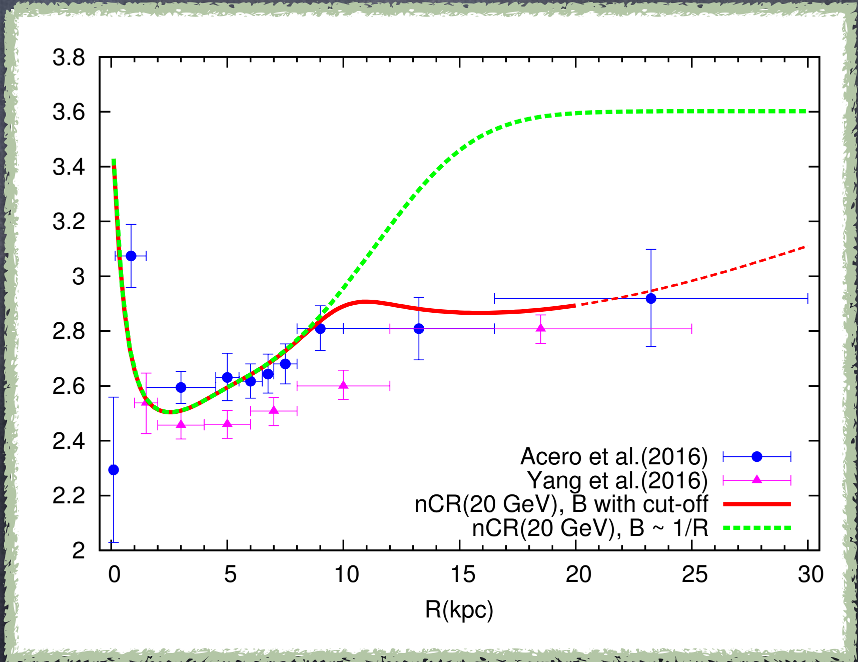
## See Talk by G. Morlino

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



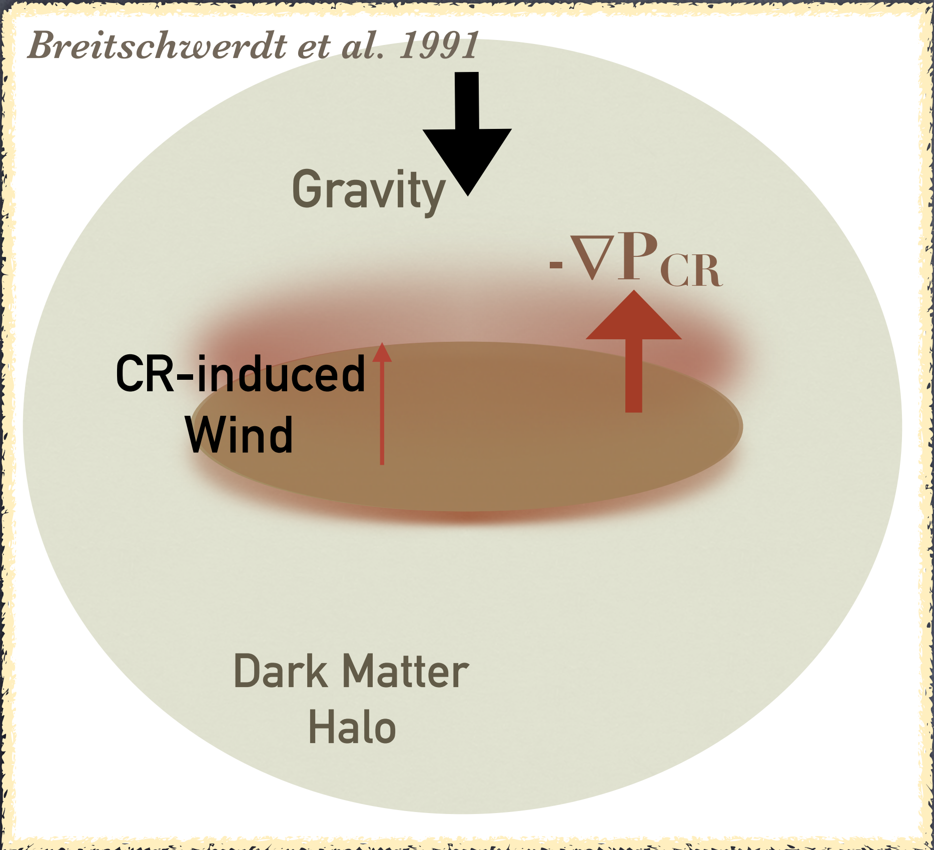

Recchia, PB & Morlino 2016

# NON LINEAR COSMIC RAY TRANSPORT:

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

Recchia, PB & Morlino, 2016 MNRAS, 462, 4227

# 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

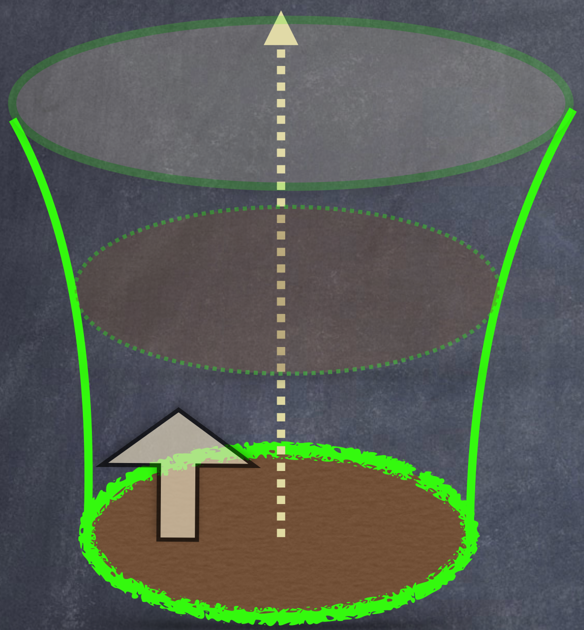
**Ptuskin et al. (1997)**: adoption of Breitschwerdt (1991) method and simplified approach to the spectrum of CRs; inclusion of Galaxy rotation.

**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:*

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

***Ptuskin et al. 1997***

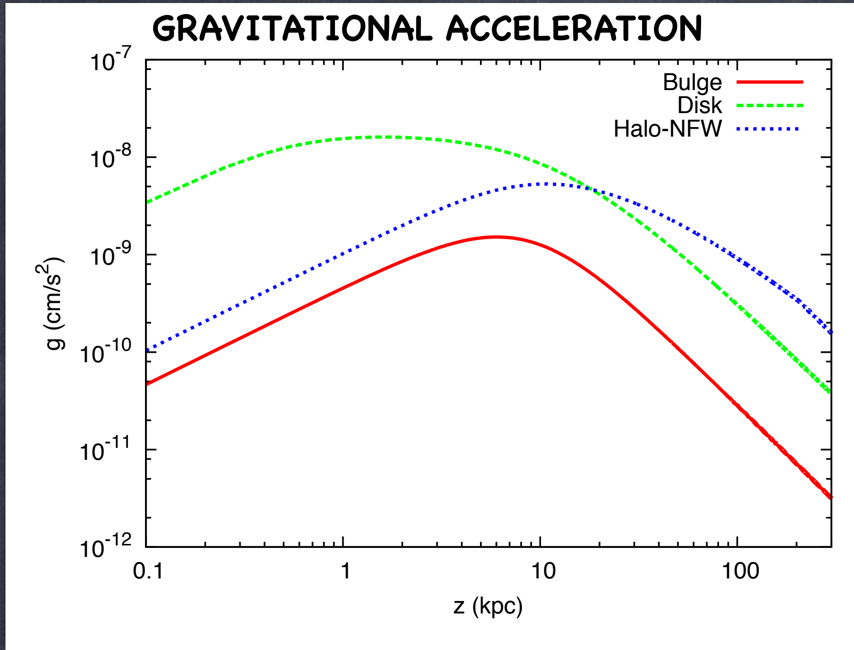
**No fixed halo size H**

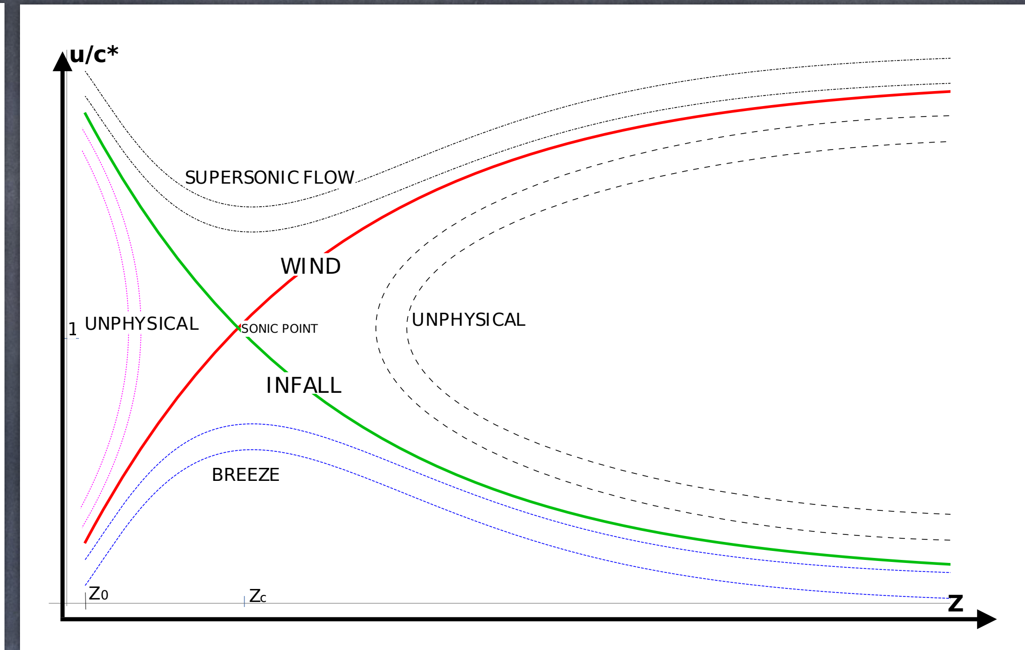
$$f_0(p) = \frac{Q(p)}{2A_{disc}} \frac{H}{D(p)} \sim E^{-\gamma-\delta} \qquad f_0(p) = \frac{Q(p)}{2A_{disc}} \frac{z_*(p)}{D(p)} \sim E^{-\gamma-\delta/2}$$

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

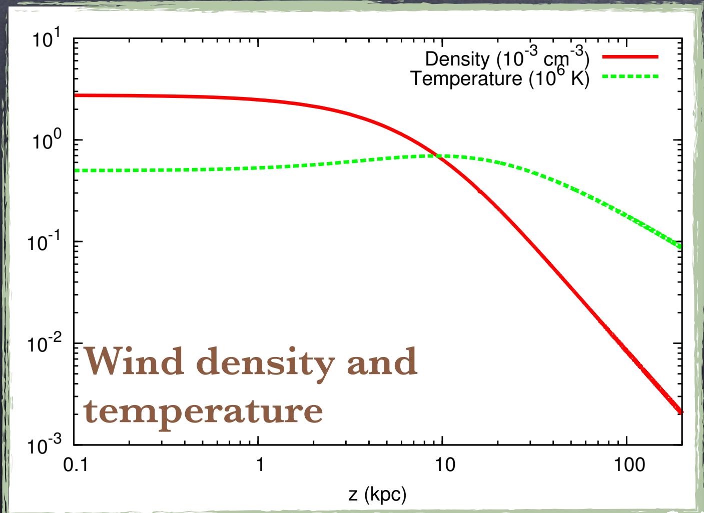
*At high energy, the critical scale becomes larger than the size of the region where the geometry of the wind remains cylindrical, and a steepening of the spectrum should be expected*

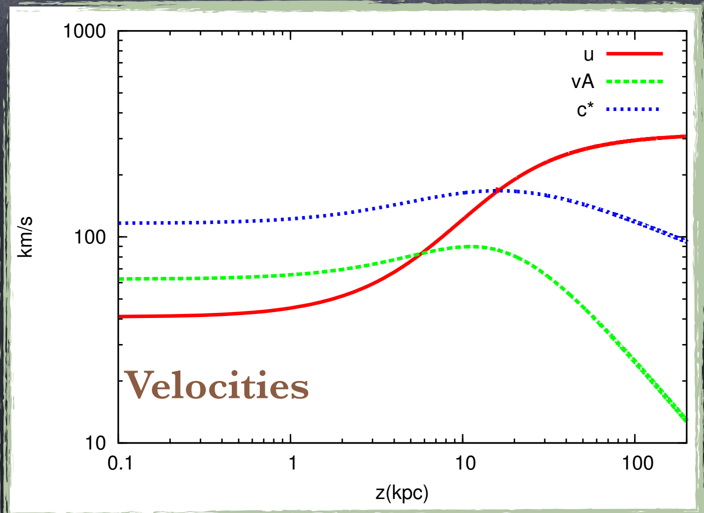
# A LOOK AT THESE CR INDUCED WINDS



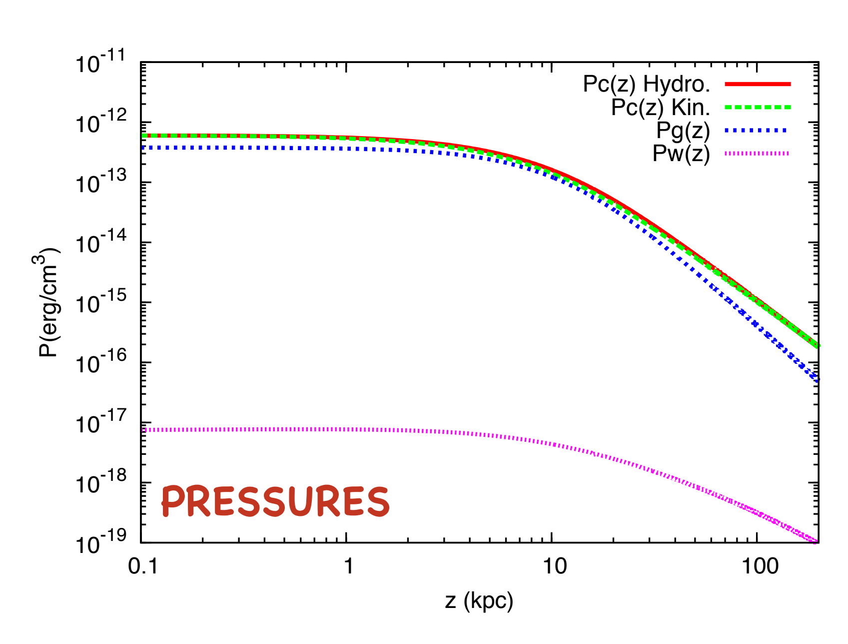



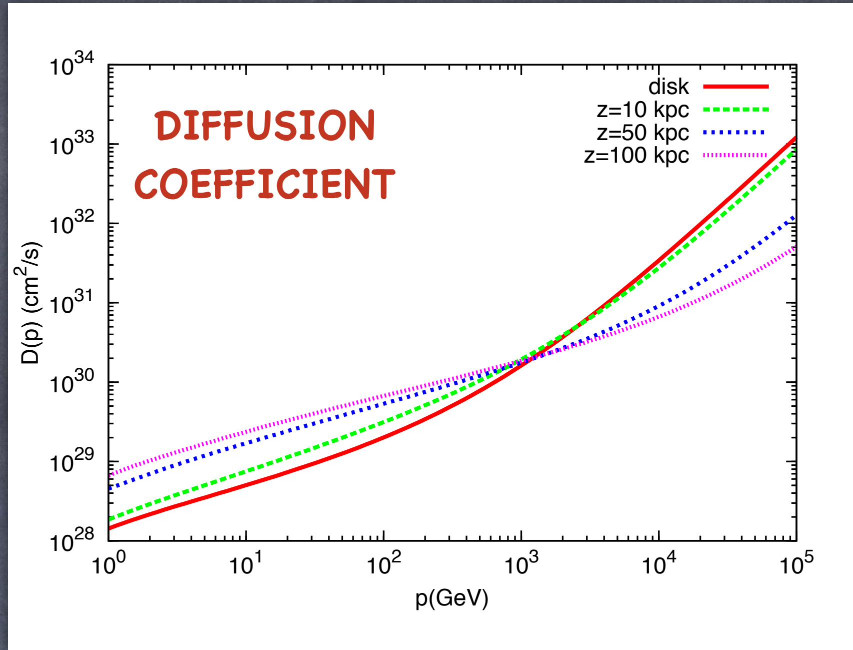

*Recchia, PB & Morlino 2016*

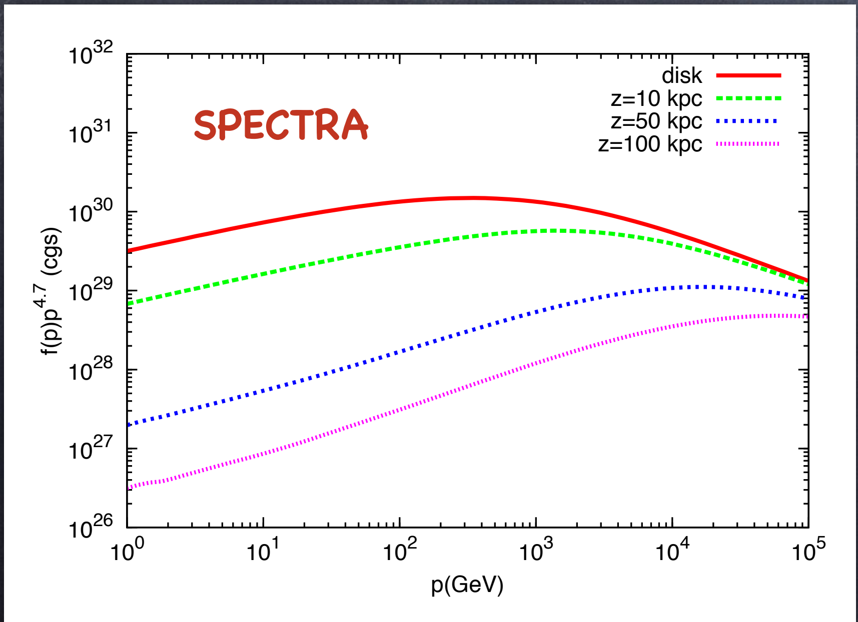


# A LOOK AT THESE CR INDUCED WINDS



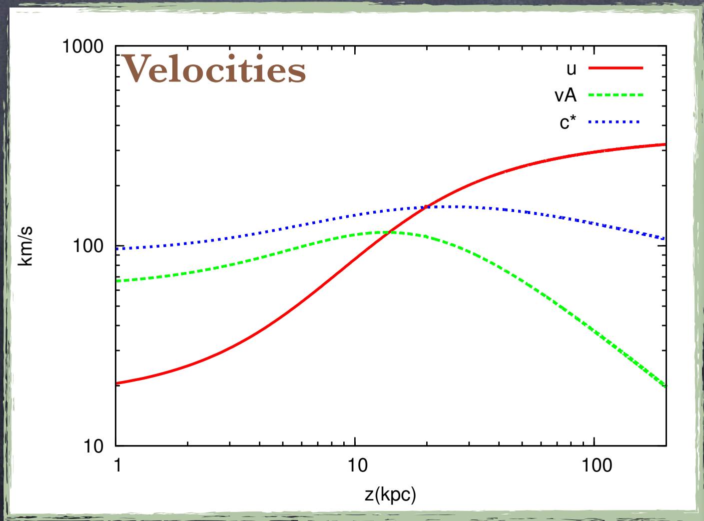

Wind solutions can be found, but they typically lead to CR spectra at the Earth that are quite unlike the observed ones...

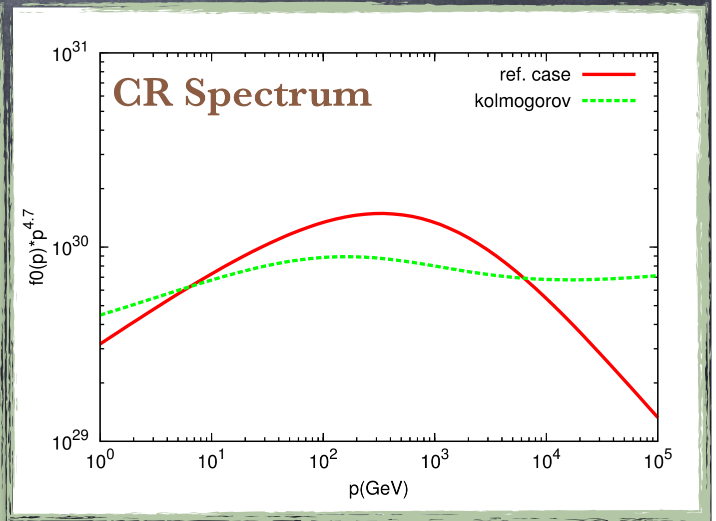
# IMPORTANCE OF THE NEAR DISC REGION

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:

## NON LINEAR COSMIC RAY TRANSPORT:

# 4) CR INDUCED INSTABILITIES AROUND SOURCES OF UHECR IN THE INTERGALACTIC MEDIUM

PB, D'Angelo & Amato, 2015 PhRvL, 115, 11101

# Limits on Accelerators of UHECRs

in the original form by Waxman (2005)

IN THE NON RELATIVISTIC CASE ONE CAN WRITE A GENERIC EXPRESSION:

$$\frac{1}{3}\frac{E(eV)}{300ZB}\frac{c}{u} = \xi R \quad \xi < 1$$

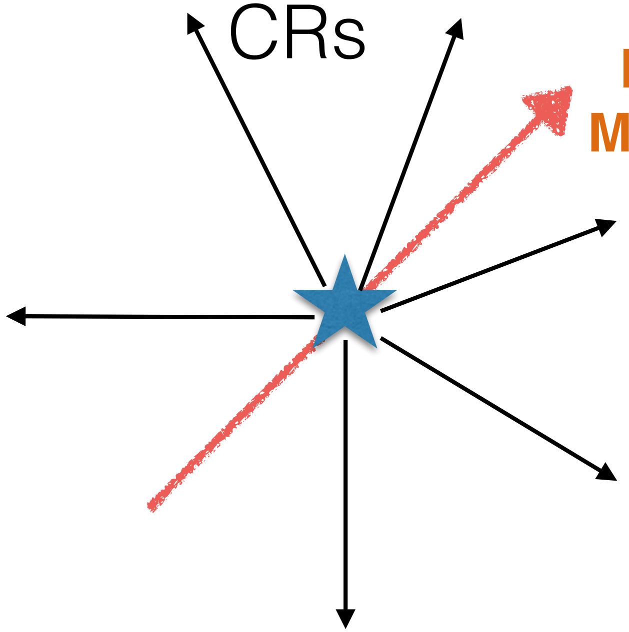
THIS IMPLIES THAT:

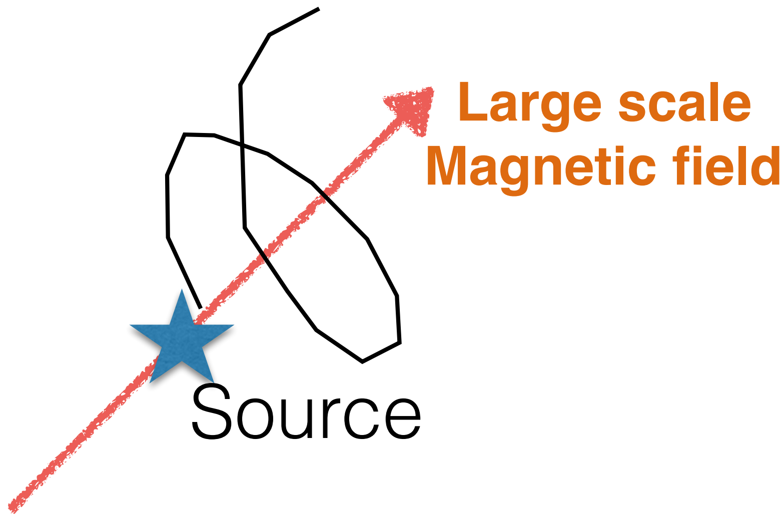
$$\epsilon_B = \frac{B^2}{4\pi} > 9.8 \times 10^{-8}\frac{E(eV)^2}{Z^2\beta^2\xi^2R^2}$$

THE SOURCE ENERGETIC MUST BE AT LEAST AS LARGE AS THE MAGNETIC ONE:

$$L = \frac{1}{2}\rho u^3 4\pi R^2 > 1.8 \times 10^{46} erg/s \left(\frac{E}{Z10^{20}eV}\right)^2 \left(\frac{\xi}{0.1}\right)^{-2} \beta^{-1}$$

# HOW DO CR ESCAPE THEIR SOURCE?



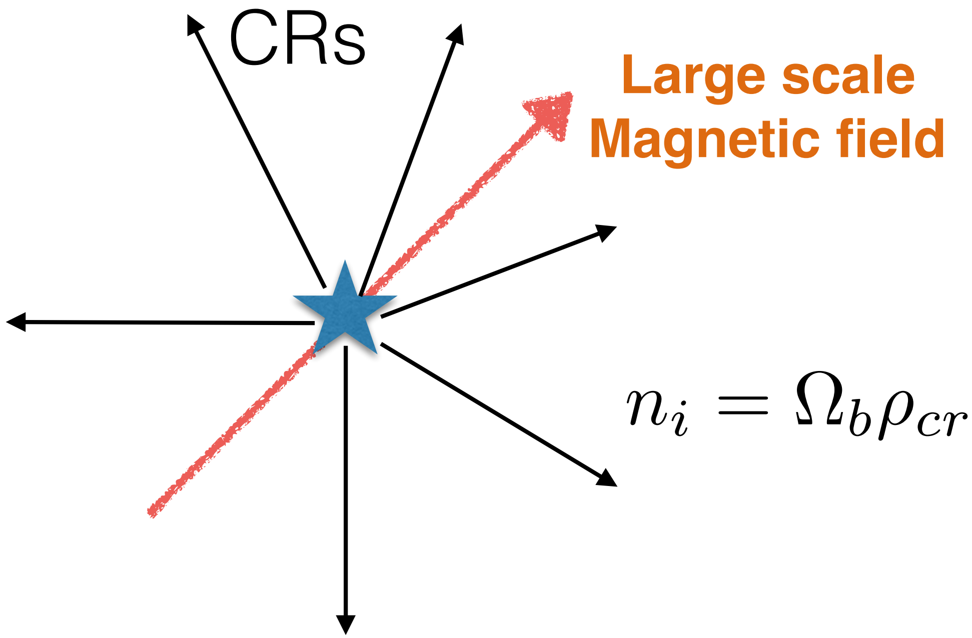

LARMOR RADIUS
>> COHERENCE LENGTH

LARMOR RADIUS
<< COHERENCE LENGTH

$$E \gtrsim 10^6 GeV\, B_{-13} \lambda_{10}$$

$$E \lesssim 10^6 GeV\, B_{-13} \lambda_{10}$$

# CASE A: BALLISTIC ESCAPE




$$n_{CR}(E,r) = \frac{q(E)}{4\pi r^2 c} = \frac{L_{CR}}{\Lambda}\frac{E^{-2}}{4\pi r^2 c} \approx$$

$$\approx 1.7 \times 10^{-14} L_{44}\, E_{\rm GeV}^{-2}\, r_{\rm Mpc}^{-2}\ {\rm cm}^{-3}{\rm GeV}^{-1}$$

$$n_i = \Omega_b \rho_{cr}/m_p \simeq 10^{-7} cm^{-3}$$

Density of cosmological baryons

THE ESCAPING CR REPRESENT AN ELECTRIC CURRENT MADE OF POSITIVELY CHARGED PARTICLES

A RETURN CURRENT IS DRIVEN TO CONSERVE CHARGE AND MAKE THE CURRENT VANISH

# CURRENT DRIVEN INSTABILITY

For the simple case of an $E^{-2}$ spectrum of CR the current in a given place can be simply written as

$$J_{CR} = e n_{CR}(>E)c = \frac{e L_{CR} E^{-1}}{4\pi\Lambda r^2}$$

Non resonant modes (*Bell 2004*) excited if: $J_{CR} E > \frac{ceB_0^2}{4\pi}$

This is equivalent to:

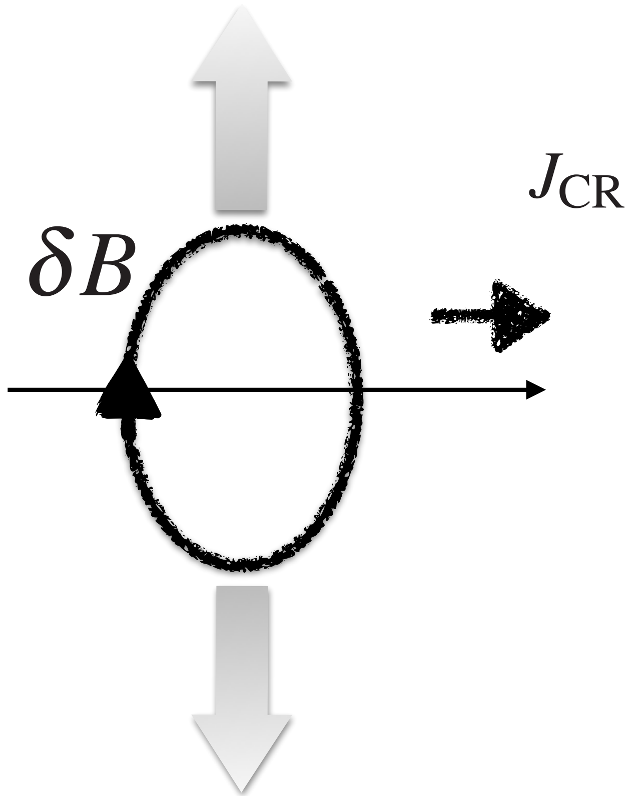
**Energy density in CR > magnetic energy density**

*THIS CONDITION IS FULFILLED WHEN:*

$$r < r_{\rm inst} = 3.7\times10^4 \frac{L_{44}^{1/2}}{B_{-13}}\ {\rm Mpc}$$

*Very large compared with the typical separation between sources*

# INSTABILITY AND SATURATION




An element of fluid is subject to a force: $J_{CR}\delta B/c$

$$\rho(dv/dt) \simeq \frac{1}{c}J_{CR}\delta B$$

where the field is being amplified:

$$\delta B(t) = \delta B_0 \exp(\gamma_{max} t)$$

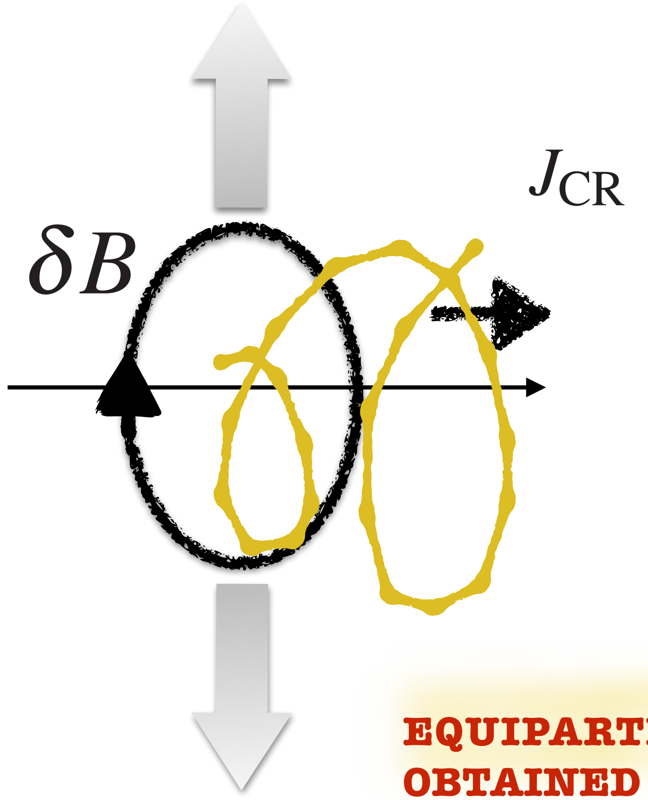
at a rate:

$$\gamma_{max} = k_{max} v_A = \sqrt{\frac{4\pi}{n_b m_p}\frac{J_{CR}}{c}}$$

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

# INSTABILITY AND SATURATION

At some point the spatial scale of the turbulent field becomes comparable with the larmor radius in δB:




$$\Delta x \sim (\delta B(t) J_{CR})(c\rho \gamma_{max}^2) \sim E/e\ \delta B(t)$$

When this happens, particles can scatter and the current gets destroyed: instability saturates

$$\frac{\delta B^2}{4\pi} \approx \frac{J_{CR} E}{ce} = n_{CR}(>E)E$$

**EQUIPARTITION BETWEEN MAGNETIC ENERGY AND CR IS OBTAINED AS AN OUTCOME OF A PHYSICAL ARGUMENT**

**ALSO: POWER SPECTRUM IS FLAT! —> BOHM SCATTERING?**

**FINAL B FIELD INDEPENDENT UPON INITIAL FIELD!!!**

# PHYSICAL CONSEQUENCES

THE INSTABILITY GROWS IF THE GROWTH TIME IS SHORTER THAN, SAY, (1/5) AGE OF THE UNIVERSE:

$$r < r_{\rm growth} = 1.2 \times 10^4 L_{44}^{1/2} E_{\rm GeV}^{-1/2}\ {\rm Mpc}$$

AND THE AMPLIFIED FIELD READS:

$$\delta B(r) = 3.7 \times 10^{-9} L_{44}^{1/2} r_{\rm Mpc}^{-1}\ {\rm Gauss}$$

IN SUCH A FIELD, PARTICLES SCATTER AND DIFFUSIVE SELF-CONFINEMENT WITHIN A DISTANCE r OCCURS FOR:

$$E \lesssim E_{\rm conf} = 2.6 \times 10^6\ r_{\rm Mpc}\ L_{44}^{1/2}\ {\rm GeV}$$

# PHYSICAL CONSEQUENCES

ONE NEEDS TO IMPOSE THAT ALL CONDITIONS ARE VERIFIED AT THE SAME TIME:

1. Non resonant instability is excited
2. It grows faster than the universe expands
3. Particles are diffusively confined

**THIS LEADS TO THE CONCLUSION THAT CONFINEMENT OCCURS FOR ENERGIES BELOW:**

$$E_{\rm cut} \approx 10^7 \text{ GeV } L_{44}^{2/3}$$

**WITHIN A DISTANCE FROM THE SOURCE:**

$$r_{\rm conf} \approx 3.8 \text{ Mpc } L_{44}^{1/6}$$

# Diffusive conditions

One could argue that the conclusion (diffusion) contradicts the initial assumption (ballistic motion), but it is not so.

For CR that are not confined within a distance r from the source:

$$\frac{1}{r^2}\frac{\partial}{\partial r}\left[r^2 D(E,r)\frac{\partial n}{\partial r}\right] = \frac{q(E)}{4\pi r^2}\delta(r) \quad \Rightarrow \quad n(E,r) \approx \frac{q}{8\pi r D(E,r)}$$

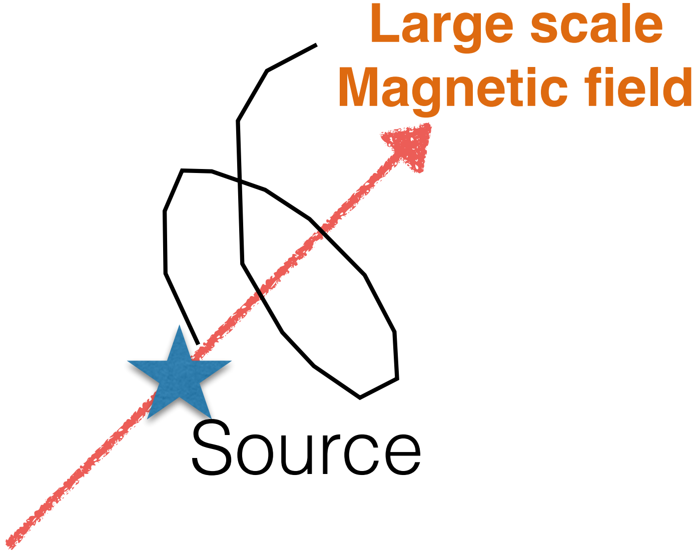
Hence the current is:

$$J_{\rm CR}^{\rm diff} = eED(E,r)\frac{\partial n}{\partial r} = e\frac{q(>E)}{4\pi r^2}$$

**exactly the same current existing in the ballistic case!!!**

**CURRENT OF ESCAPING PARTICLES DETERMINES THE FIELD**

# CASE B: MAGNETIZED PARTICLES




$$E \lesssim 10^6 GeV\, B_{-13} \lambda_{10}$$

CALCULATIONS ARE A BIT DIFFERENT BUT QUALITATIVELY SIMILAR

1. Non resonant instability is excited
2. It grows faster than the universe expands
3. Particles are diffusively confined

$$E < E_{\rm cut} = 2.2 \times 10^8 {\rm GeV}\, L_{44}^{1/4}\, B_{-10}^{1/2}\, \lambda_{10}$$ Confinement energy

$$r_{\rm conf} \approx 10\ {\rm Mpc}\ \lambda_{10}$$ Confinement radius

$$\delta B \approx 3 \times 10^{-9} {\rm G}\, L_{44}^{1/4}\, B_{-10}^{1/2}\, \lambda_{10}^{-1}$$ Magnetic field

# 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

7. NL EFFECTS AROUND EXTRAGALACTIC SOURCES MAY LEAD TO LOW ENERGY FLUX SUPPRESSION