NON-LINEAR SELF-GENERATED TURBULENCE

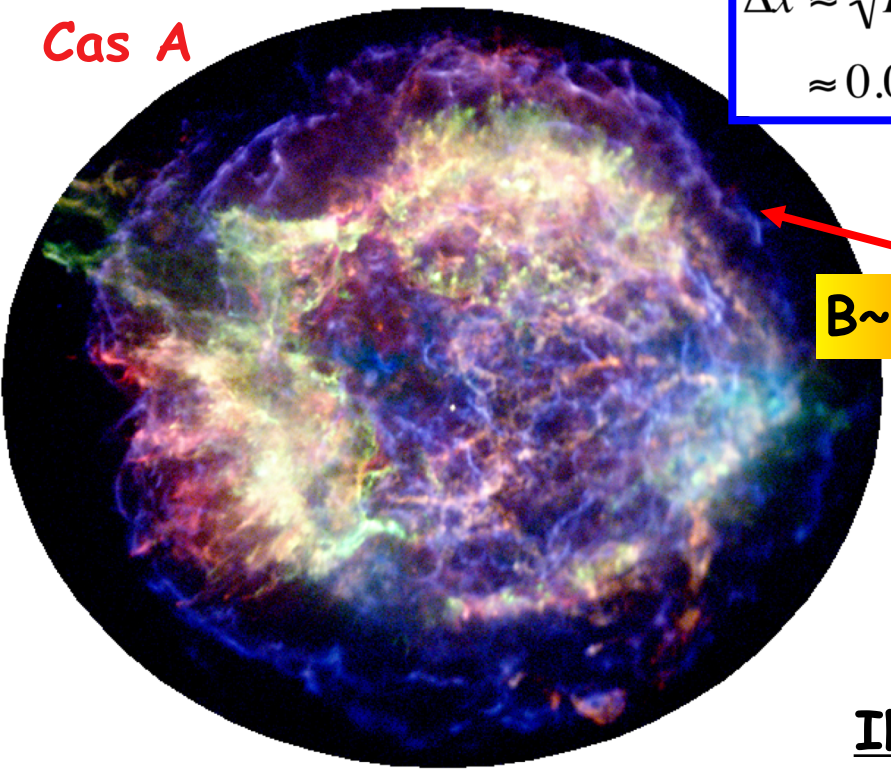
Elena Amato

INAF-Osservatorio Astrofisico di Arcetri

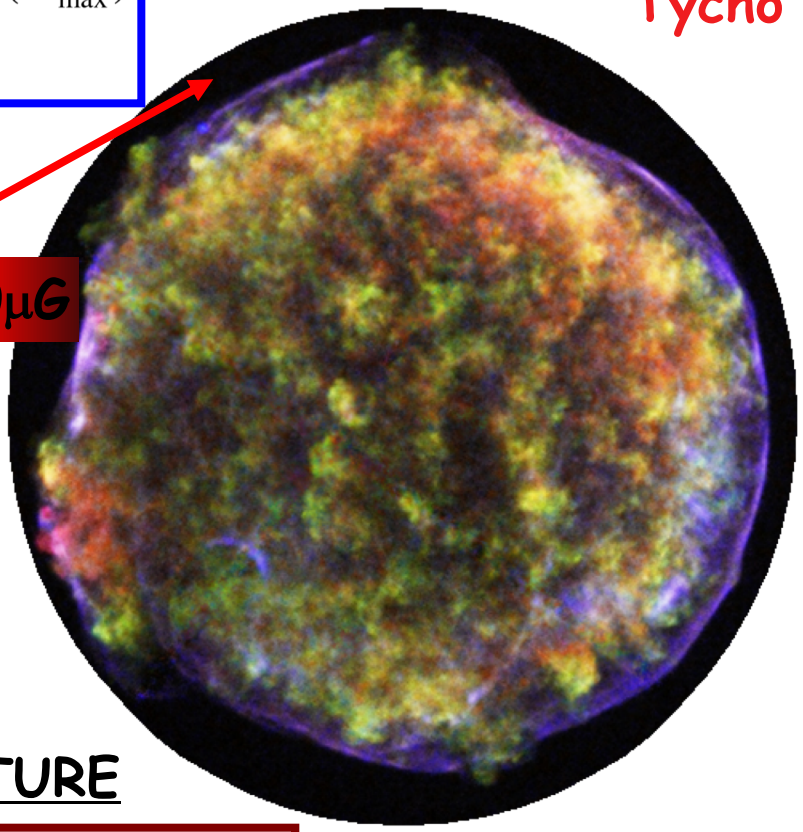
AMPLIFIED MAGNETIC FIELDS

$$\Delta x \approx \sqrt{D(E_{\max})\tau_{loss}(E_{\max})} \approx 0.04 B_{100}^{-3/2} pc$$

Cas A



Tycho



B~100-300μG

IN THE SIMPLEST PICTURE

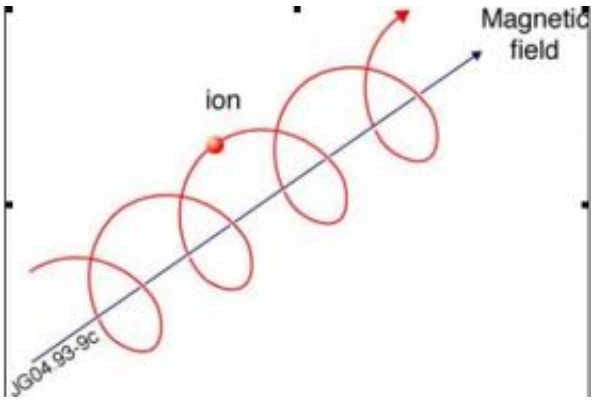
EFFICIENT PARTICLE ACCELERATION BECAUSE OF HIGH B-FIELD

HIGH B-FIELD BECAUSE OF EFFICIENT PARTICLE ACCELERATION

SELF-GENERATION OF TURBULENCE

CR PARTICLE INTERACTING WITH LOW FREQUENCY WAVE ALONG MEAN FIELD

PITCH ANGLE SCATTERING



SPATIAL DIFFUSION

$$D(p) = \frac{4}{3\pi}\left(\frac{B_0}{\delta B}\right)^2 v r_L$$

INTERACTION MOST EFFECTIVE AT RESONANCE: $\lambda \sim r_L$

BEFORE SCATTERING: $P_{CR}=n_{CR}m\gamma_{CR}v_d$

AFTER SCATTERING: $P_{CR}=n_{CR}m\gamma_{CR}v_A$

$$\frac{dP_{CR}}{dt} = \frac{n^*_{CR} m \gamma_{CR}(v_d - v_A)}{\tau}$$

$$\gamma_w = \frac{\pi}{4}\frac{n^*_{CR}}{n_i}\Omega_0\frac{(v_d - v_A)}{v_A}$$

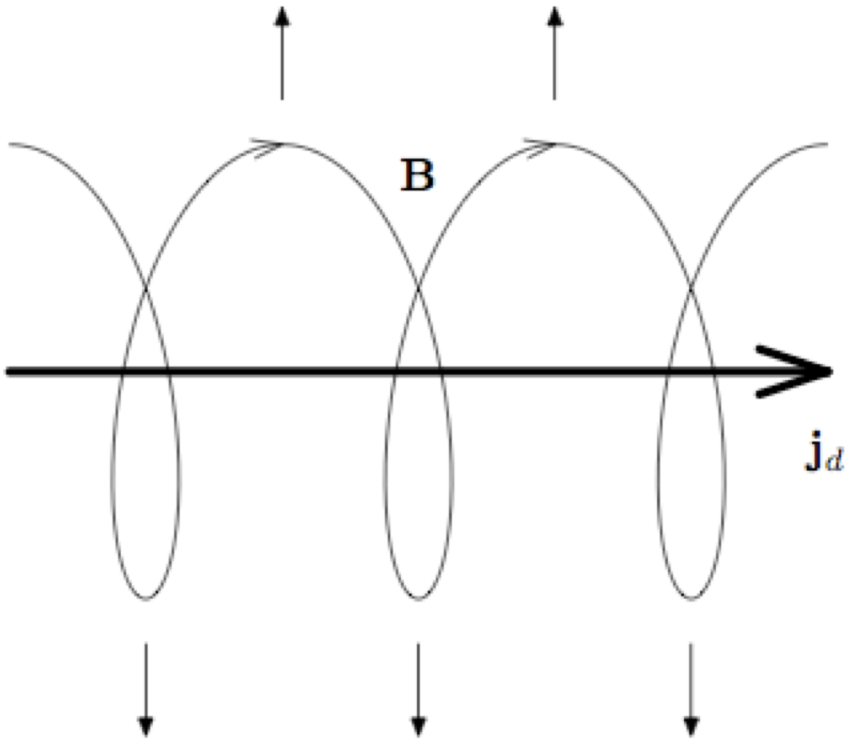
with

$$n^*_{CR} = n_{CR}\left(p > \frac{eB}{ck}\right)$$

SUPERALFVÉNIC STREAMING OF CRs ⇒ WAVE GROWTH

NON-RESONANT STREAMING INSTABILITY

(BELL INSTABILITY)



FROM Zirakashvili & Ptuskin 08

BASIC PHYSICAL PICTURE (Bell 04)

- CR CURRENT INDUCES COMPENSATING CURRENT IN PLASMA
- $\vec{J}_{\rm ret} \wedge \vec{B}$ INDUCES TRANSVERSE PLASMA MOTION
- RESULTING CURRENT ACTS AS A SOURCE OF B
- FOR RIGHT-HAND POLARIZED WAVES, FIELD LINES ARE STRETCHED: FIELD IS AMPLIFIED

RESONANT VS NON-RESONANT

NON-RESONANT MODE ONLY EXISTS WHEN

$$\frac{4p}{c} J_{CR} > \left| \frac{B_0}{r_{L,0}} \right|$$

OR

$U_{CR}/U_B > c/v_D$

$$k_{\max} = \frac{4pJ_{CR}}{2cB_0} >> \frac{1}{r_{L,0}}$$

$$\Gamma_{\max} \approx v_A k_{\max} >> \frac{v_A}{r_{L,0}} >> W$$

GROWS FASTER ON SMALL SCALES
BUT THEN INVERSE CASCADE
(Riquelme & Spitkovsky 09, Bykov + 13)
LEADS TO
BOHM TYPE SPECTRUM (Caprioli & Spitkovsky 14)

RESONANT

$$\delta B_{\rm sat} \approx B_0$$

SATURATION MAGNETIC FIELD

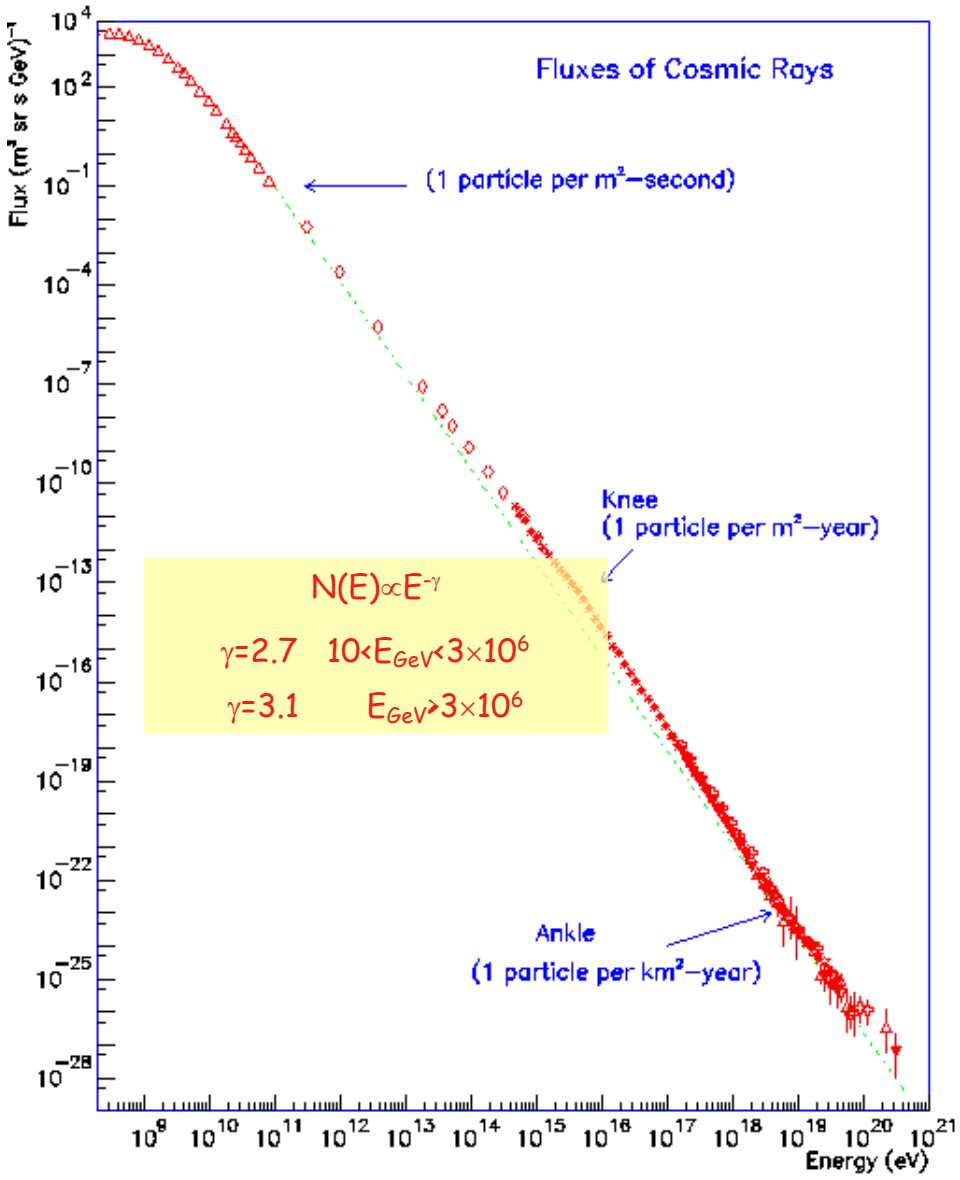
NON-RESONANT

$$\frac{\delta B^2_{\rm sat}}{4\pi} \approx \frac{v_d}{c} U_{\rm CR}$$

OR

$$\delta B^2_{\rm sat} \approx \frac{L_{\rm CR}}{c\ \Lambda\ R^2}$$

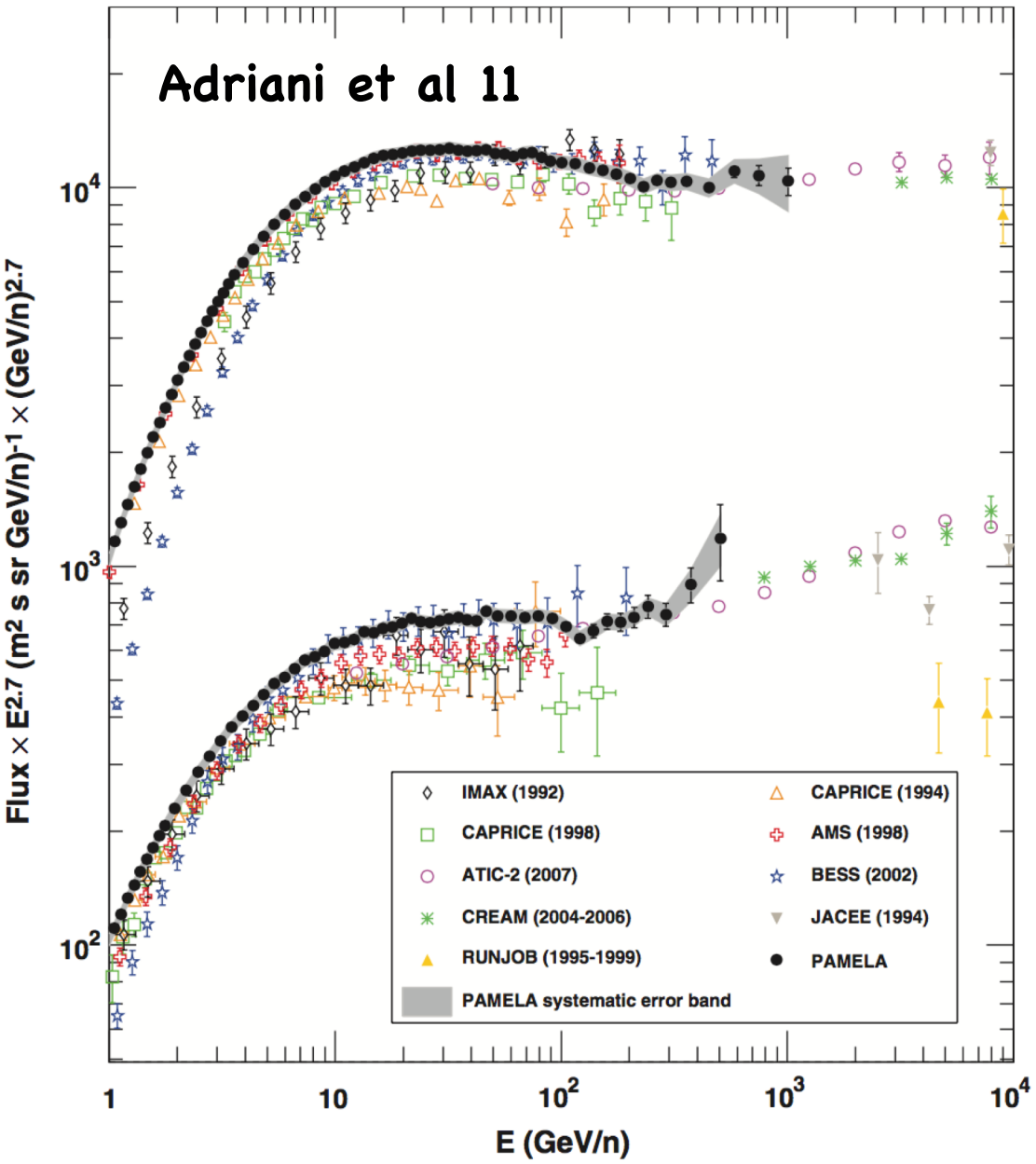
SPECTRAL BREAKS

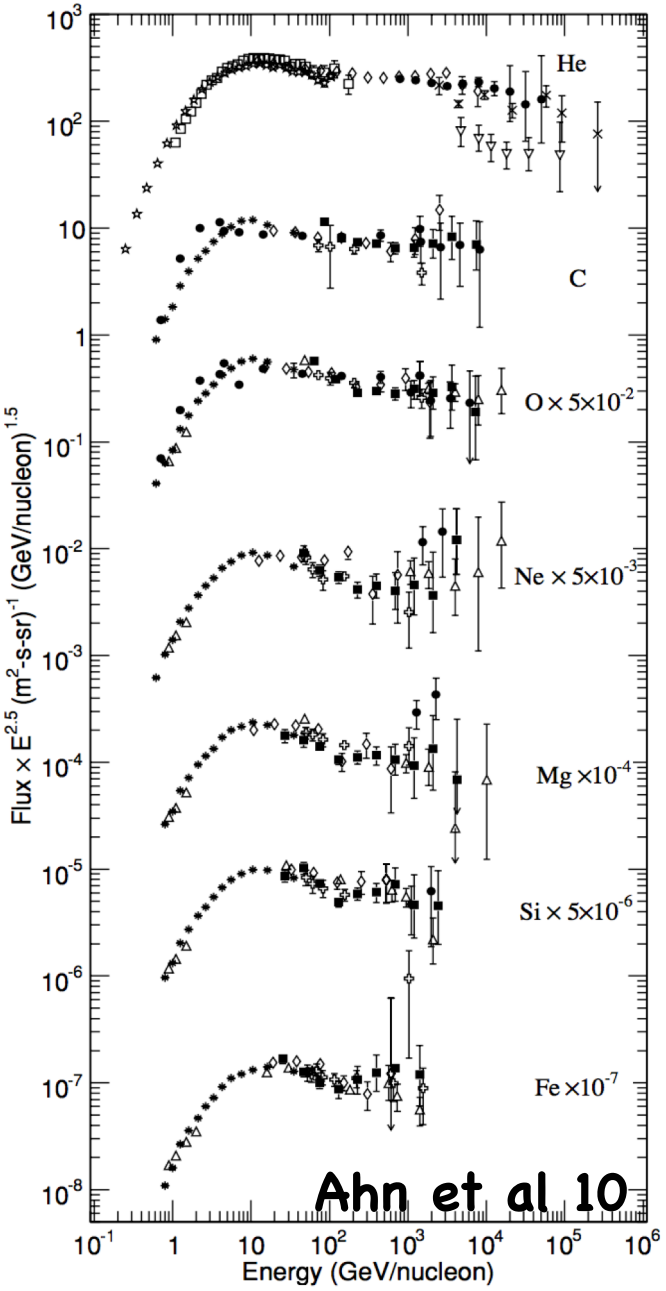


FOR A LONG TIME ONLY KNEE AND ANKLE

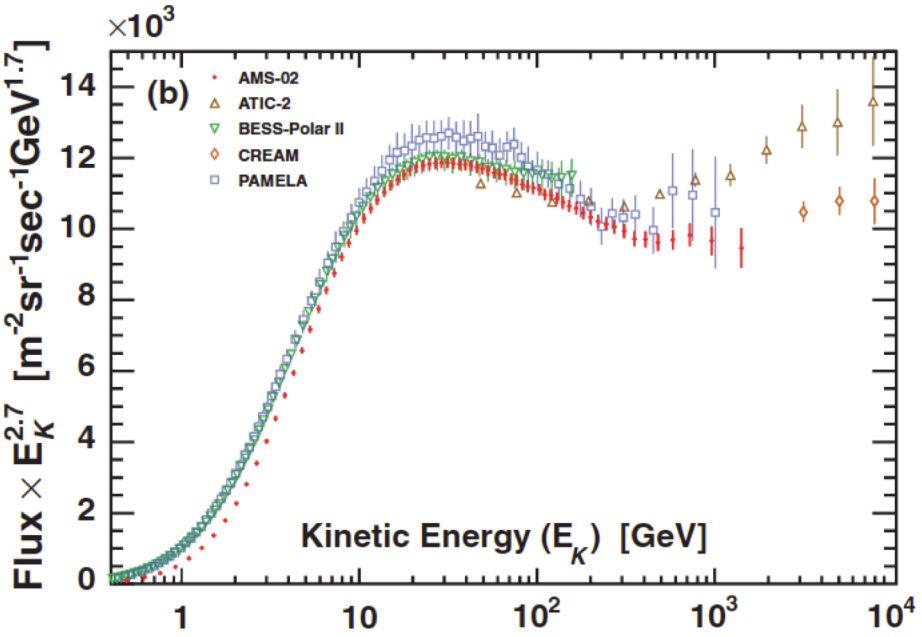
THE GALACTIC COMPONENT USED TO HAVE A FEATURELESS SPECTRUM

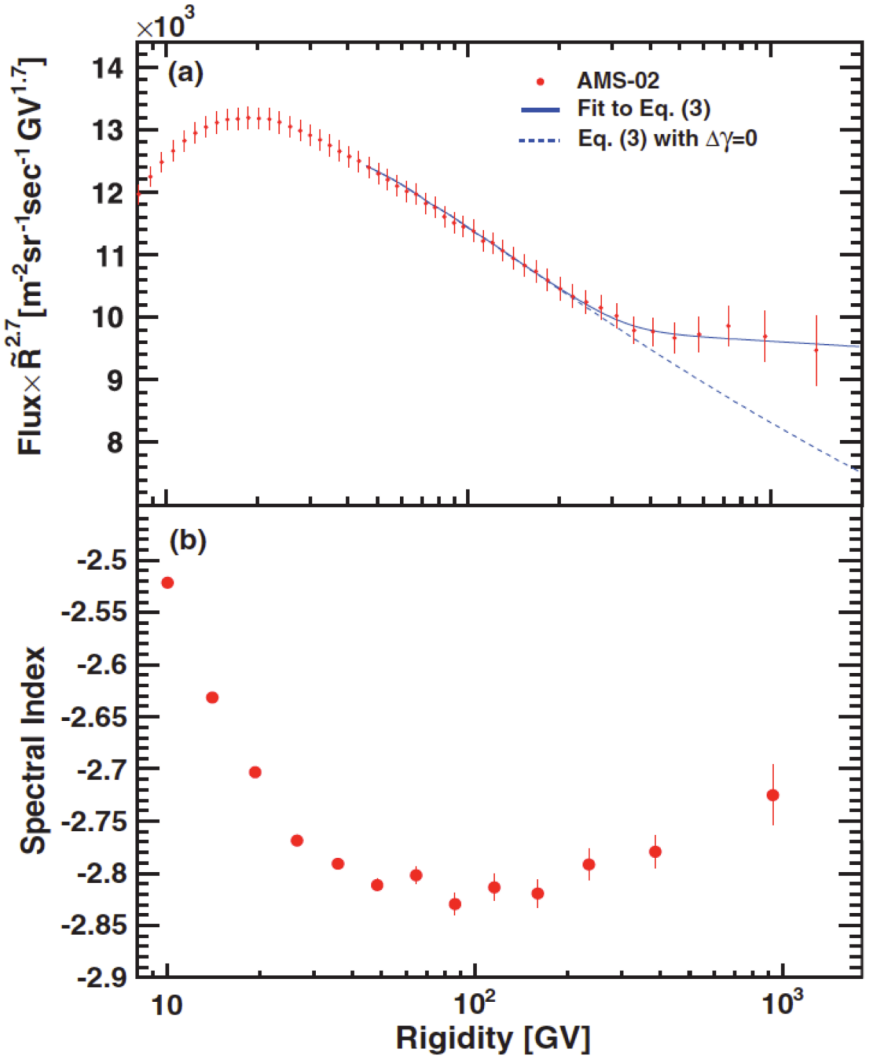
SPECTRAL BREAKS





AMS02 CONFIRMS





$$\Phi_p = C\left(\frac{R}{45GV}\right)^{\gamma}\left[1+\left(\frac{R}{R_0}\right)^{\Delta\gamma/s}\right]^{s}$$

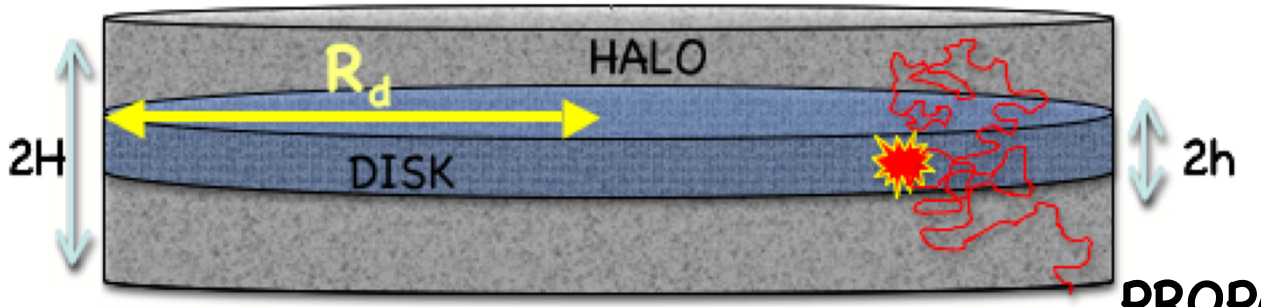
$$\gamma = -2.849 \qquad \Delta\gamma = 0.133$$

$$R_0 = 336\ GV$$

Aguilar et al 15

WHAT ARE THEY TELLING US?

H INDEP. OF E



INJECTION

$$N_S(E) \propto E^{-\gamma_{inj}}$$

PROPAGATION

$$D(E) \propto E^{\delta_e}$$

STEADY STATE $N_p(E) = Q(E)\tau_{\rm esc}$

LEAKY BOX MODEL $\tau_{\rm esc}(E) \approx \dfrac{H^2}{D(E)} \propto E^{-\delta_e}$

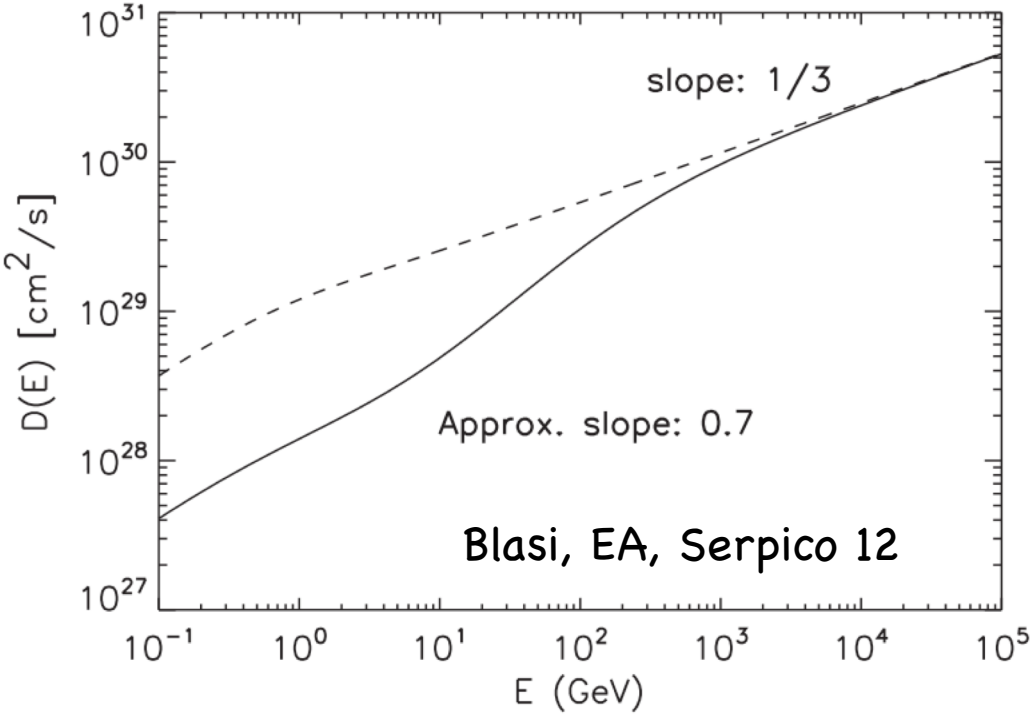
PROTON SPECTRUM $N_{\rm p}(E) = \dfrac{N_S(E)\mathcal{R}}{2\pi R_d^2 H}\tau_{\rm esc} \propto E^{-\gamma_{\rm inj}-\delta_{\rm e}}$

BREAKS MIGHT BE TELLING US ABOUT INJECTION OR DIFFUSION...

BREAK FROM SELF-GENERATED TURBULENCE

THAT LOW ENERGY CRs COULD SELF-GENERATE THE TURBULENCE FOR THEIR SCATTERING IS AN OLD SUGGESTION (e.g. Wentzel 74)

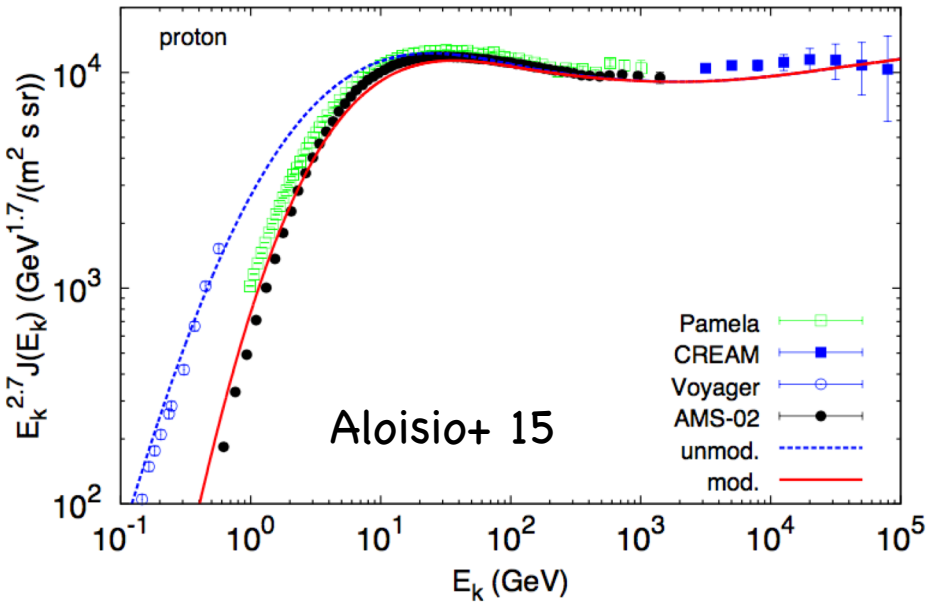
UP TO WHAT SCALE/ENERGY SELF-GENERATED WAVES ARE DOMINANT?

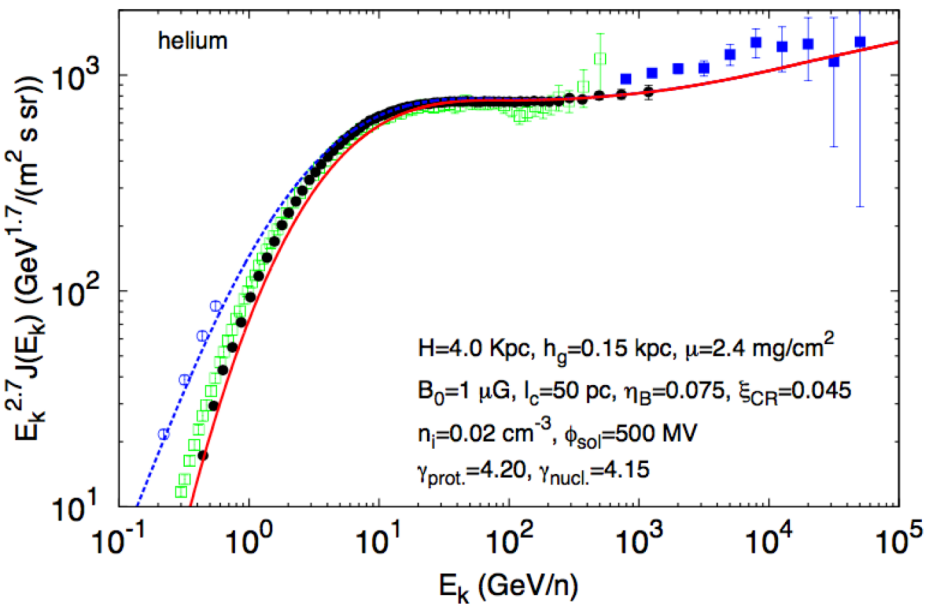


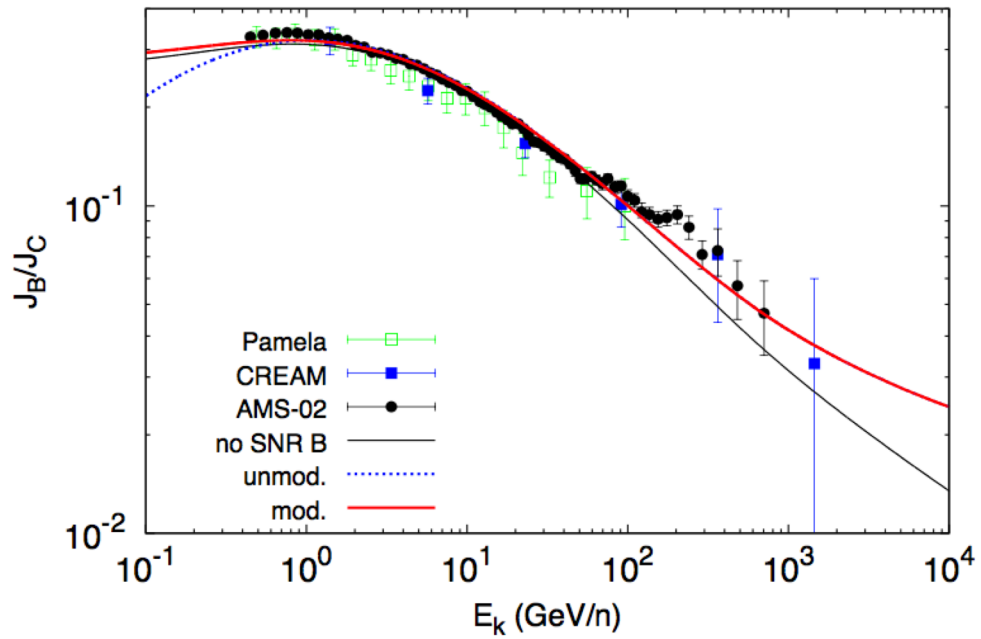
$$W_{ext}(k_{TR}) = W_{CR}(k_{TR}) \qquad k_{TR}\, r_L(E_{TR}) = 1$$

$$E_{TR} = 228\ GeV \left(\frac{R_{d,10}^2\ H_3^{-1/3}}{\xi_{0.1}\ E_{51}\ \mathcal{R}_{30}} \right)^{3/2(\gamma_p - 4)} B_{0,\mu}^{(2\gamma_p - 5)/2(\gamma_p - 4)}$$

TAKING ALL INTO ACCOUNT..



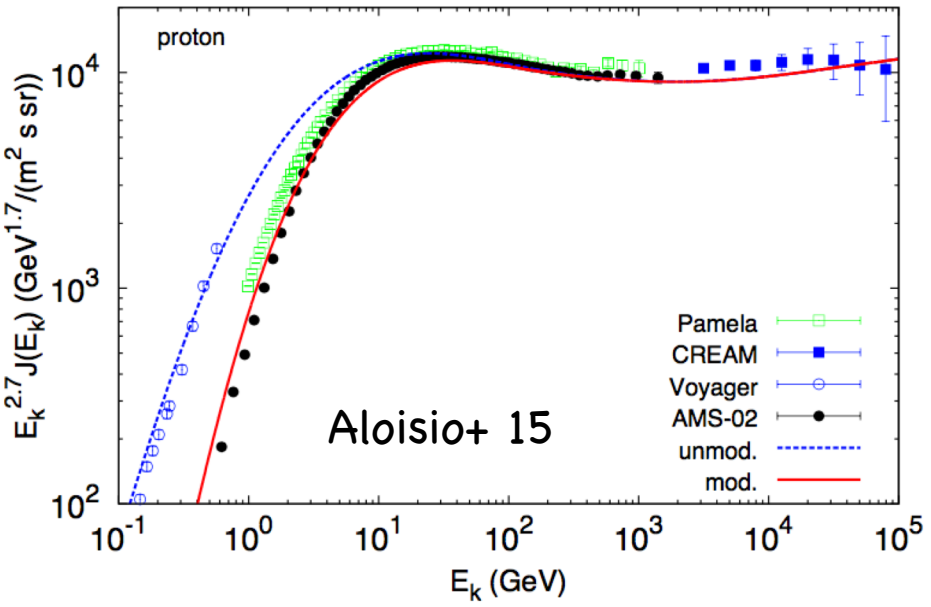


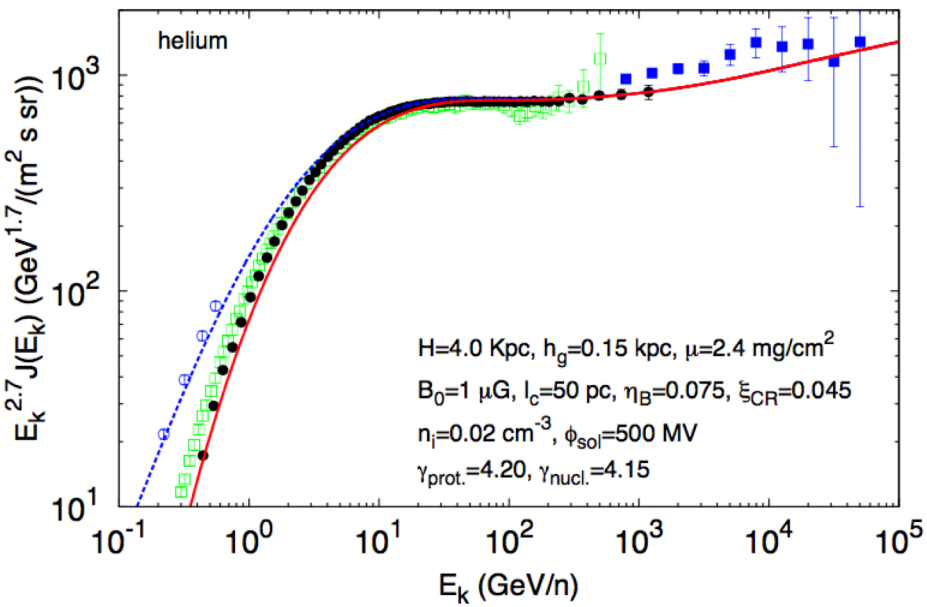


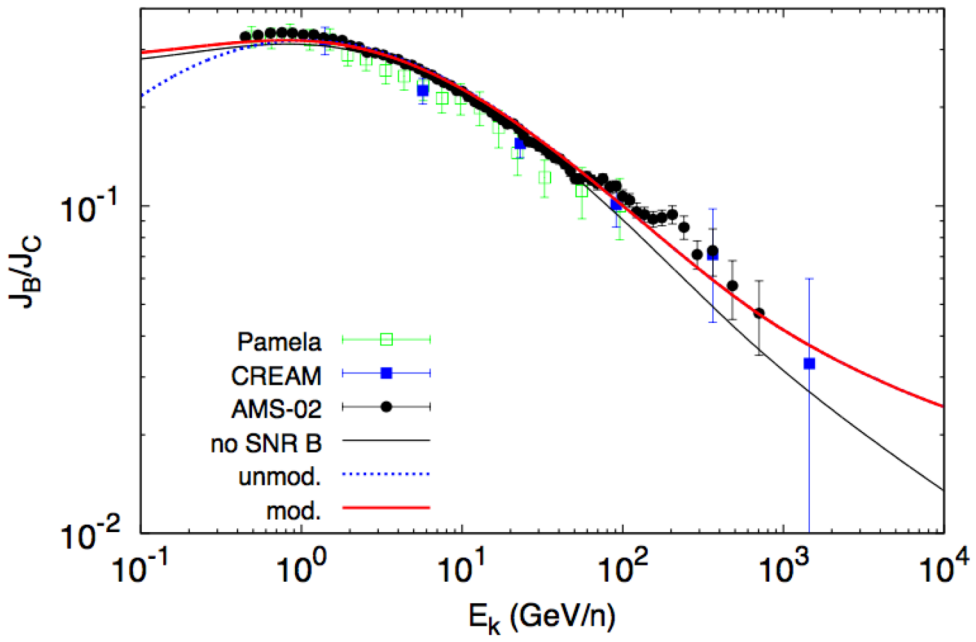
AMS02 DATA ON SECONDARIES CONFIRM THAT BREAKS ARE RELATED TO TRANSPORT RATHER THAN INJECTION: SECONDARIES HARDEN MORE!

(Aguilar+ 18)

TAKING ALL INTO ACCOUNT..







IMPLICATION:

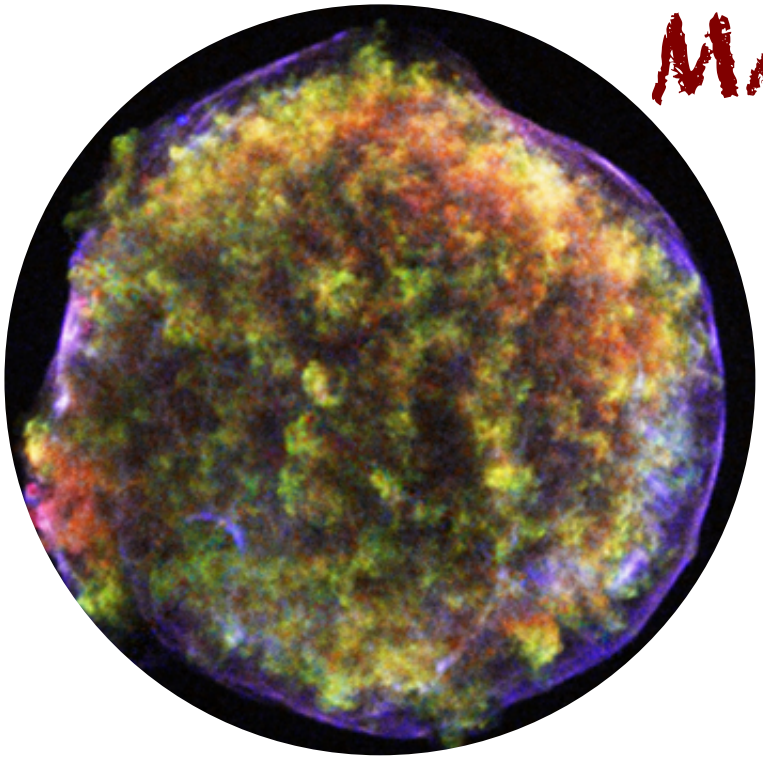
AT TEV ENERGIES CRs ARE INJECTED IN THE GALAXY WITH A $E^{-2.3/2.4}$ SPECTRUM

- ✓ OK WITH AMS-02 B/C
- ✓ GOOD FOR ANISOTROPY

(e.g. Blasi&EA 12)

- X BAD FOR MAX. EN. IN SNRs

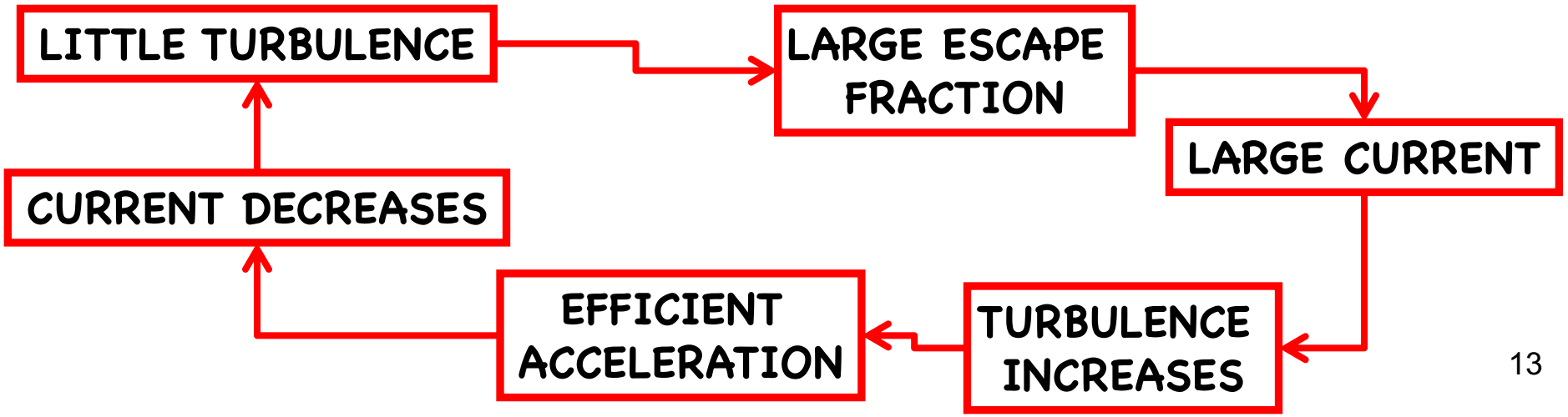
(Schure & Bell 13; Cardillo, EA, Blasi 15)



MAXIMUM ENERGY IN SNRs

- MFA (Bell 04) DUE TO CURRENT OF ESCAPING PARTICLES
- GROWTH RATE PROPTO J_{CR} WHICH DEPENDS ON SPECTRUM AT THE SHOCK, P_{MAX} AND V_S (Schure & Bell 13, Cardillo, EA, Blasi 15)

SELF-REGULATION MECHANISM



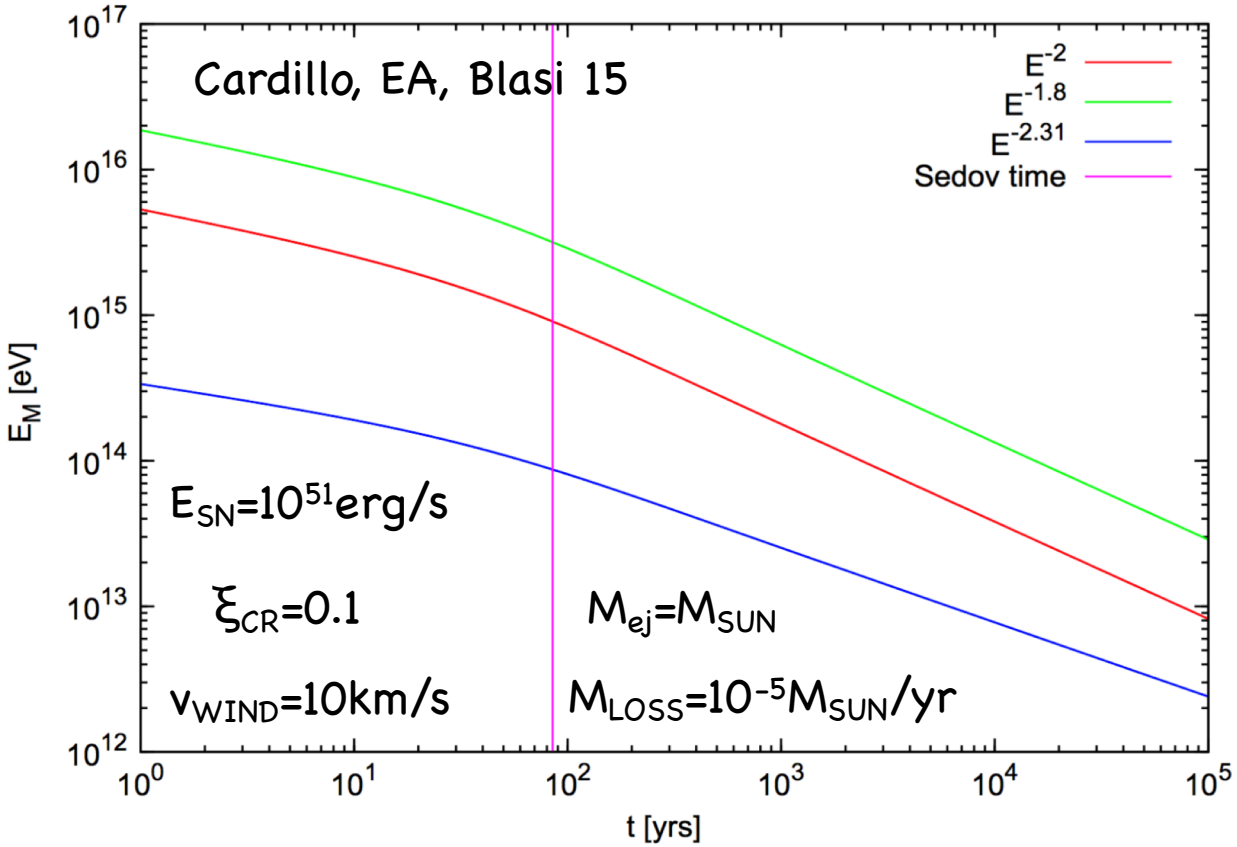
PEVATRONS

TYPE I

$$E_M \approx 130 \left(\frac{\xi_{\rm CR}}{0.1}\right) \left(\frac{M_{\rm ej}}{M_\odot}\right)^{-\frac{2}{3}} \left(\frac{E_{\rm SN}}{10^{51}{\rm erg}}\right) \left(\frac{n_{\rm ISM}}{{\rm cm}^{-3}}\right)^{\frac{1}{6}} {\rm TeV}$$

TYPE II

$$E_M \approx 1 \left(\frac{\xi_{\rm CR}}{0.1}\right) \left(\frac{M_{\rm ej}}{M_\odot}\right)^{-1} \left(\frac{E_{\rm SN}}{10^{51}{\rm erg}}\right) \left(\frac{\dot{M}}{10^{-5} M_\odot {\rm yr}^{-1}}\right)^{\frac{1}{2}} \left(\frac{v_w}{10{\rm km/s}}\right)^{-\frac{1}{2}} {\rm PeV}$$



RELEASED SPECTRUM

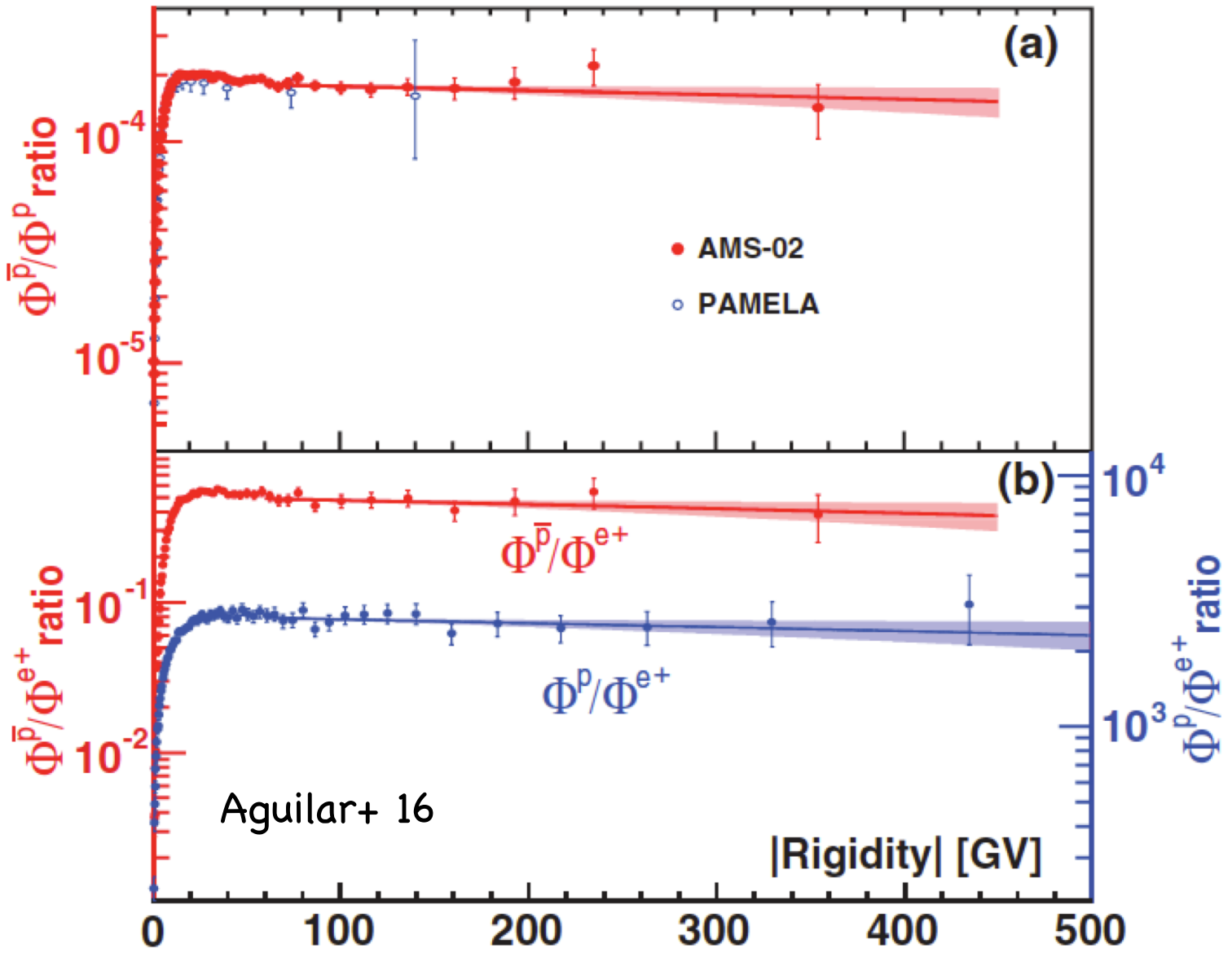
$\Gamma_{CR} > 2$ IF $\Gamma_{SRC} > 2$

$\Gamma_{CR} = 2$ IF $\Gamma_{SRC} \leq 2$

WITH $\Gamma_{CR} > 2$, P_{max}=PeV REQUIRES:

- **RARE** (<1/1000 yr^{-1})
- **EXTREME EVENTS** ($E_{SN} > 10^{52}$erg)
- **EXTREME EFFICIENCY** ($\xi_{CR} > 30\%$)

ODDITIES OF ANTIMATTER



SECONDARIES VS PRIMARIES: EXPECTATION

SPECTRUM OF PRIMARIES

$$N_{\rm prim}(E) \propto E^{-\gamma_{\rm inj}-\delta_e}$$

SPECTRUM OF STABLE SECONDARIES

$$N_{\rm sec}(E) \approx N_{\rm prim}(E) c n_H \sigma_{\rm sp} \tau_{\rm esc} \propto E^{-\gamma_{\rm inj}-2\delta_e}$$

$$\frac{\Phi_B}{\Phi_C} \propto E^{-\delta_e}$$

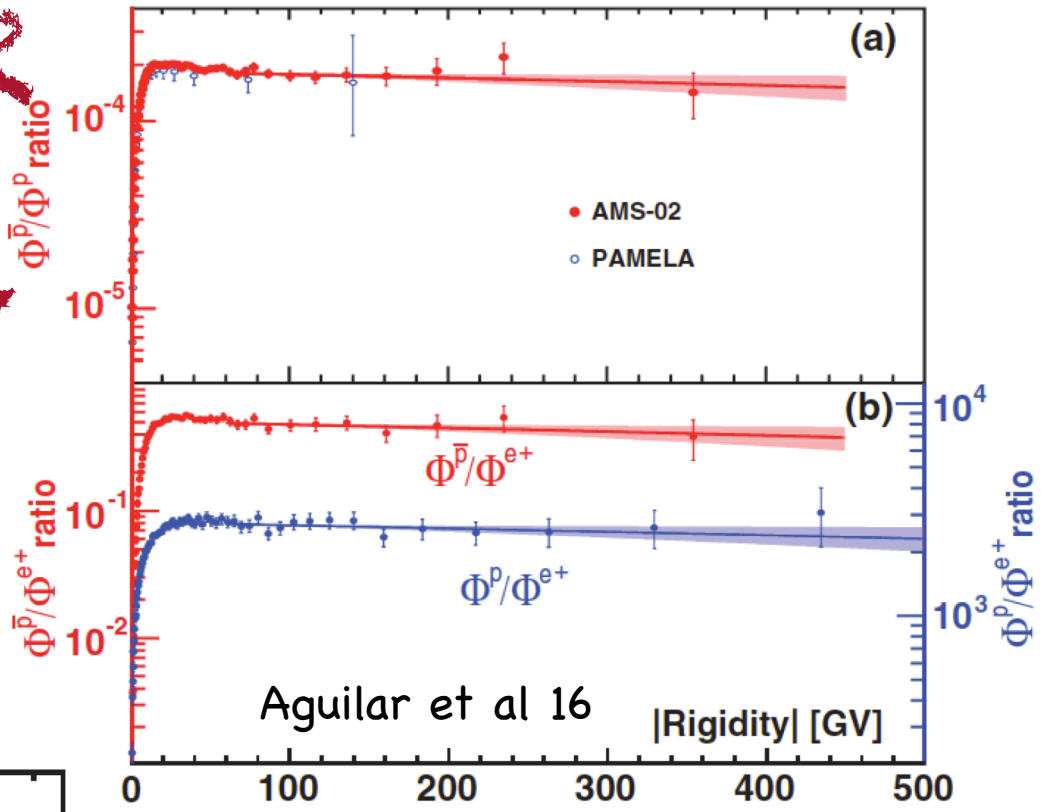
ANALOGOUSLY

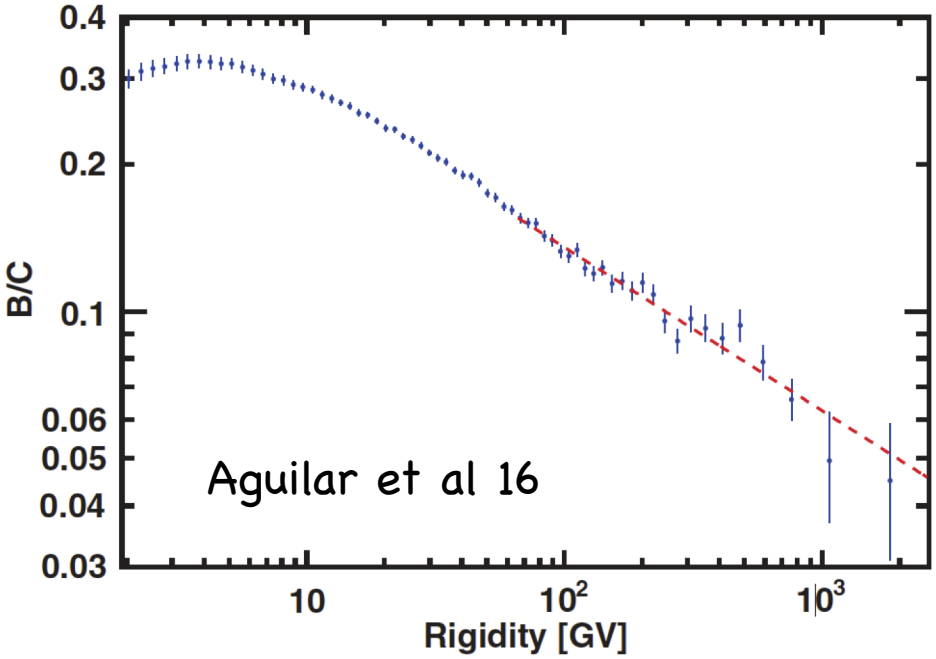
$$\frac{\Phi_{\bar{p}}(E)}{\Phi_p(E)} \propto E^{-\delta_e}$$

AND WITH EXTRA ASSUMPTION THAT ELECTRONS' $\gamma_{\rm INJ}$ SAME AS PROTONS

$$\frac{\Phi_{e^+}}{\Phi_{e^+}+\Phi_{e^-}} \approx \frac{\Phi_{e^+}}{\Phi_{e^-}} \propto E^{-\delta_e}$$

ANTIMATTER VS SECONDARY NUCLEI





B/C IS WELL BEHAVED: DECREASES WITH ENERGY

anti-p/p AND e^+/p DO NOT

ALTERNATIVE SCENARIOS

DECOUPLING B PRODUCTION FROM THE REST

(Blum et al 10; Katz et al 13; Cowsik & Burch 10; Cowsik et 1l 14; Lipari 16)

- CR ESCAPE FROM GALAXY IS ENERGY INDEP.

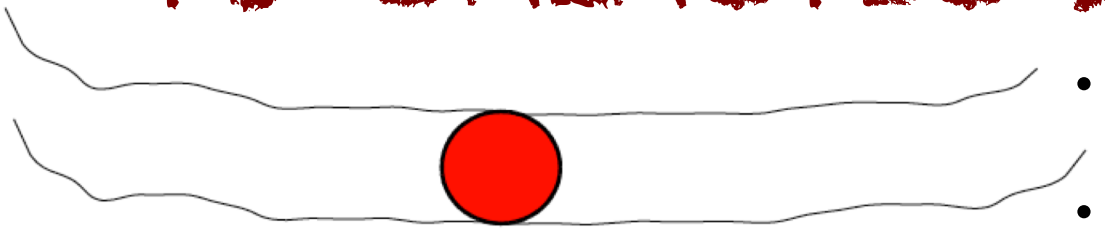
- LOW ENERGY CRS ACCUMULATE LARGE GRAMMAGE IN SOURCE VICINITY: B PRODUCED CLOSE TO THE SOURCE
  ➔B/C STANDARD

- POSITRONS AND ANTI-P FROM 10-20 TIMES LARGER ENERGY P
  ➔ SAME SPECTRA AS PARENT P

NON-LINEAR CONFINEMENT?

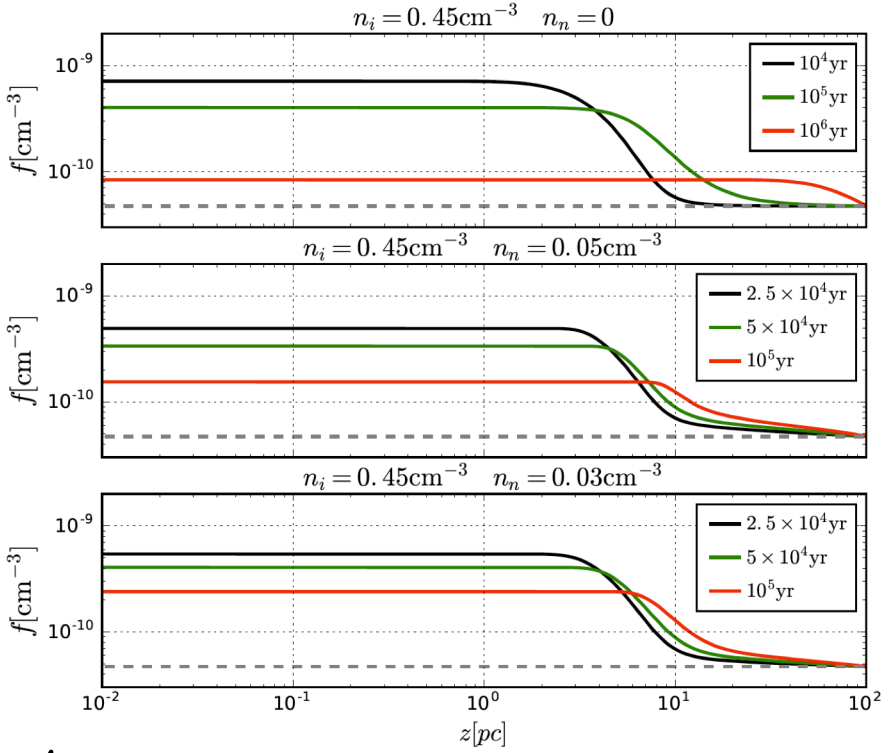
- LOW ENERGY PARTICLES CAN SPEND A LONG TIME CLOSE TO THEIR SOURCES THANKS TO SELF-GENERATED TUBULENCE, IN PRINCIPLE BOTH ***RESONANT*** ($E_{CR}/U_B<c/v_s$) AND ***NON-RESONANT*** (Bell 04)($E_{CR}/U_B>c/v_s$)

WAVE-GENERATION CLOSE TO GALACTIC SOURCES

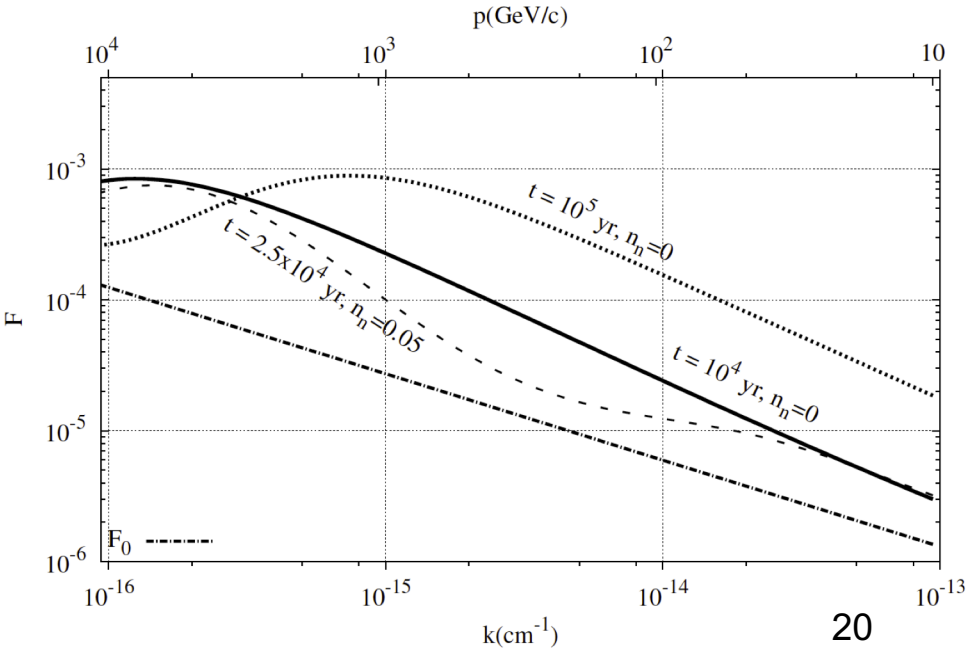


- RELEASE CRs WITH 0.1 E_{SN} IN 10^4 YR
- LET THEM PROPAGATE IN SELF-GEN. FIELD

1GeV CR OVERDENSITY

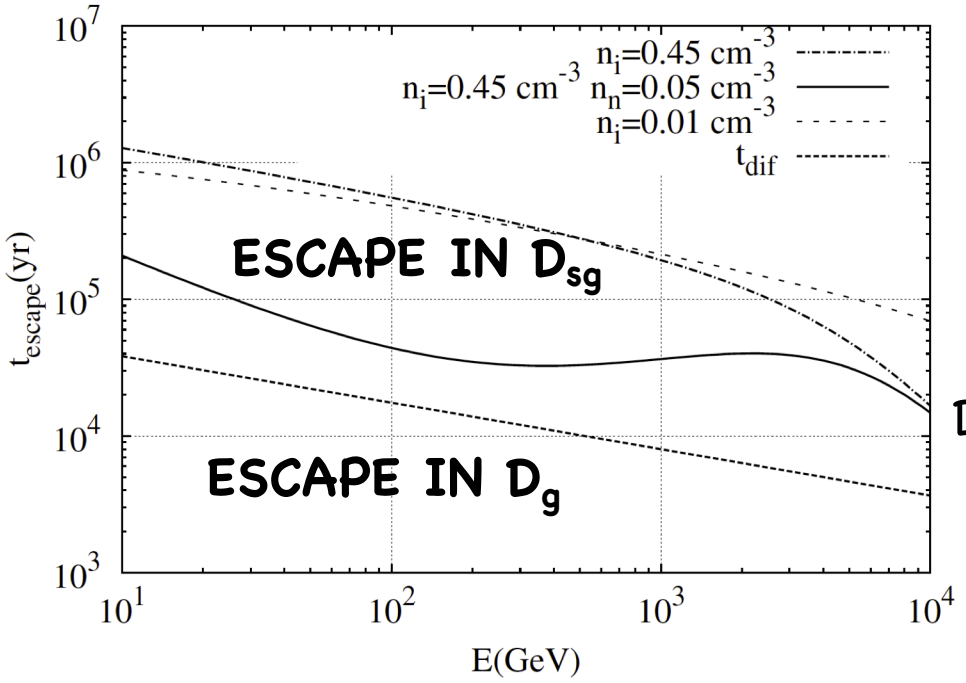


WAVE ENERGY DENSITY (50pc)

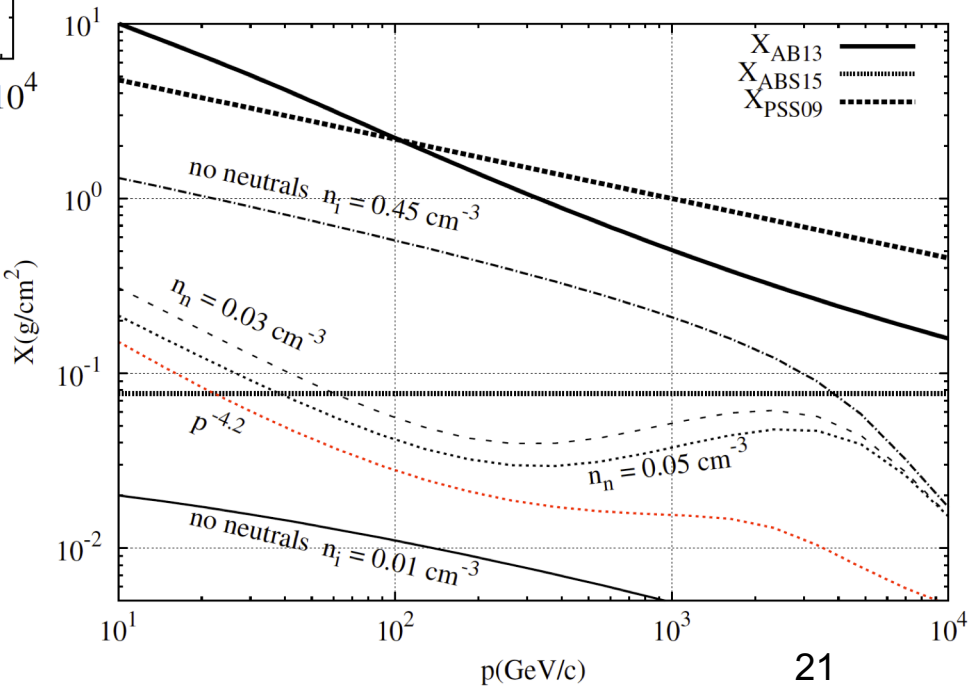


D'Angelo, Blasi, EA 16

SELF-CONFINEMENT AROUND GALACTIC SOURCES



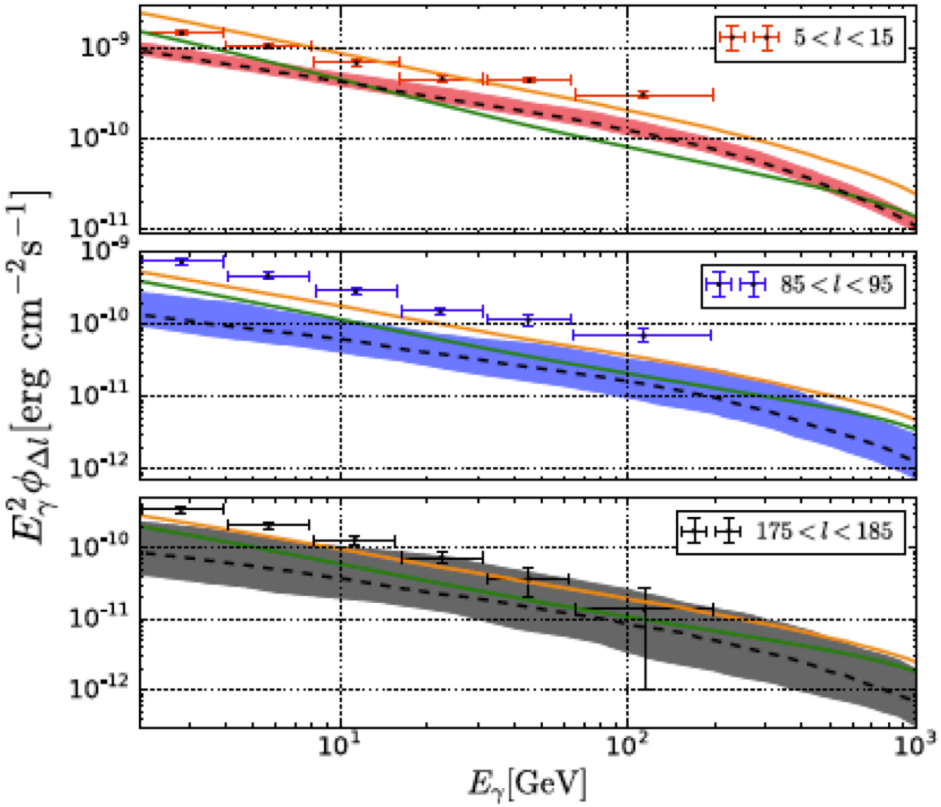
D'Angelo, Blasi, EA 16

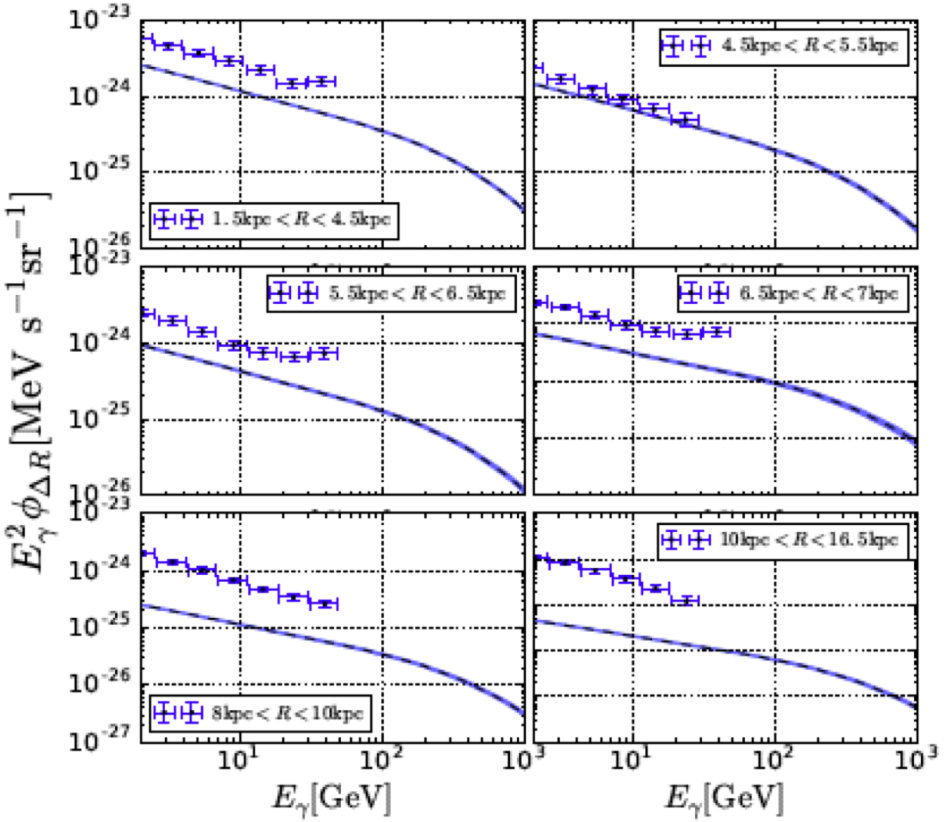


- **NON-NEGLIGIBLE GRAMMAGE CAN BE ACCUMULATED IN THE SOURCE VICINITY**

- **CRITICALLY DEPENDS ON IONIZATION FRACTION**

DIFFUSE GAMMA RAY EMISSION





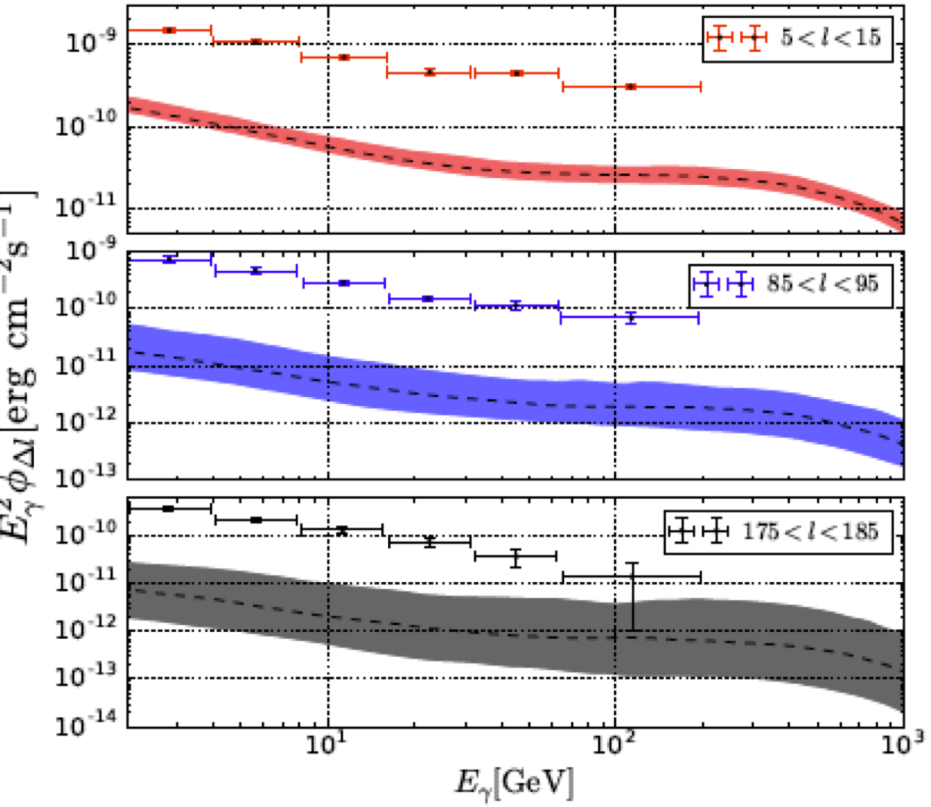
COMPARISON WITH FERMI ANALYSIS BY Yang et al 16

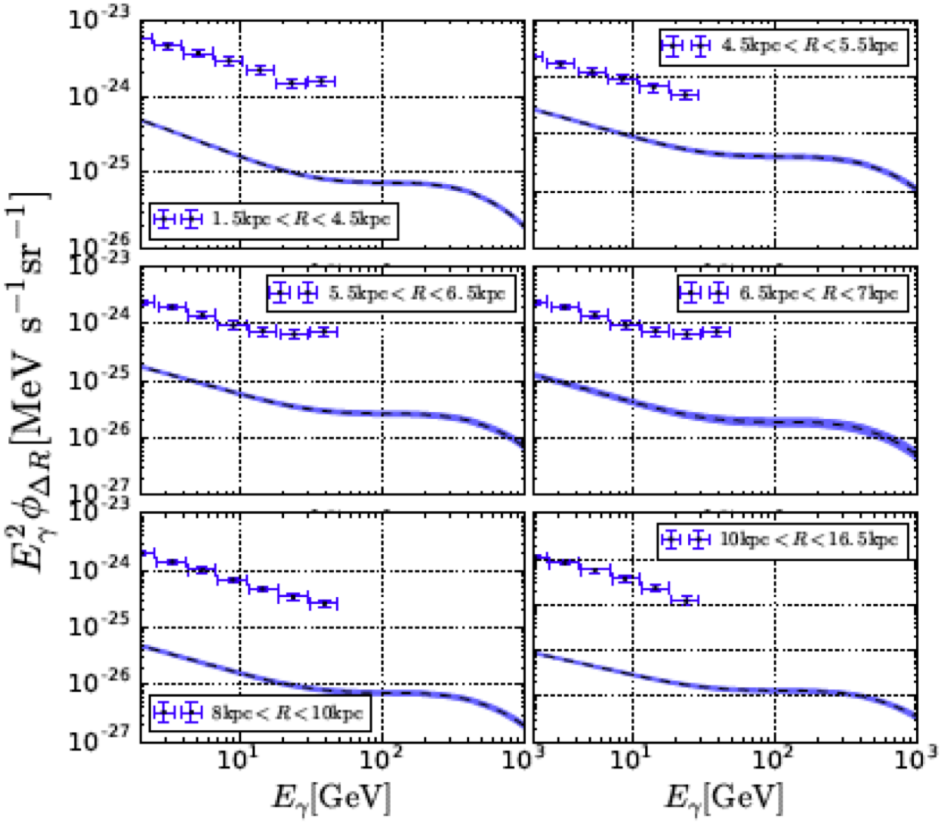
n_i =0.45
n_n =0

(D'Angelo+ 18)

COMPARISON WITH FERMI ANALYSIS BY Acero et al 16

DIFFUSE GAMMA RAY EMISSION





COMPARISON WITH FERMI ANALYSIS BY Yang et al 16

n_i =0.45
n_n =0.05

(D'Angelo+ 18)

COMPARISON WITH FERMI ANALYSIS BY Acero et al 16

NON-RESONANT CONFINEMENT?

PROPAGATION FROM EXTRAGAL. SOURCES

LOW IGM B-FIELD → **NON-RES INSTABILITY VERY EFFICIENT**

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

BOHM LIKE DIFFUSION IN nG STRENGTH FIELD

- **10^{18} eV PARTICLES** (WEAK DEPENDENCE ON SOURCE LUMINOSITY ETC.) **CONFINED CLOSE TO THEIR SOURCES** (WITHIN A DISTANCE OF A FEW Mpc) **FOR THE AGE OF THE UNIVERSE** (Blasi, EA, D'Angelo 15)

➔**LOW ENERGY CUT-OFF IN EXTRAGAL. CRs????**

NON-RESONANT CONFINEMENT?

ESCAPE FROM THE MILKY WAY

AS B-FIELD DROPS ESCAPING CRS EXCITE NON-RES INSTABILITY

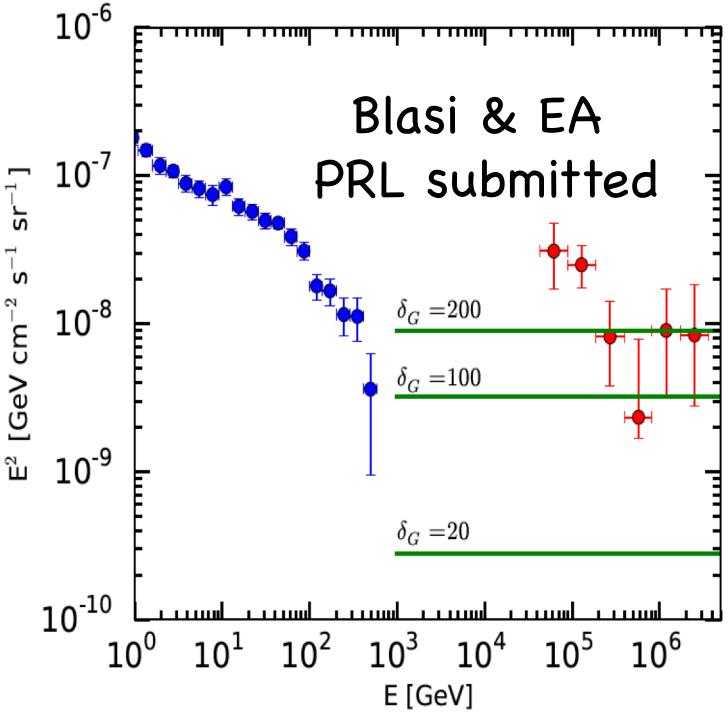
PARTICLE CONFINEMENT CREATES PRESSURE GRADIENT THAT SETS BACKGROUND PLASMA INTO MOTION

SATURATION WHEN

$V_D \sim V_{BG} \sim V_A \sim 100$ km/s

$$B \sim 2 \times 10^{-8}\ G\ L_{41}^{1/2}\ R_{10}^{-1}$$

NEUTRINOS?



NON-STANDARD SCENARIOS REALLY NEEDED TO EXPLAIN SECONDARY TO PRIMARY RATIOS?

NOT FOR NUCLEI AND ANTIPROTONS!

QUALITATIVELY

- FLAT DIFFUSION COEFFICIENT
- FLATTENING IN IN PARENT PROTONS SPECTRUM
- INCREASEE OF PRODUCTION CROSS SECTION WITH ENERGY

→ ANTI-P SPECTRA FLATTER THAN SECONDARY NUCLEI

REACCELERATION AND SOURCE GRAMMAGE

PARTICLES ENCOUNTERING A SHOCK DURING PROPAGATION ARE REACCELERATED
(Blasi 17)

NO EFFECT ON PRIMARY SPECTRA
BUT
FLATTENING OF SECONDARIES

$$f_0(p) = s\frac{\eta n_1}{4\pi p_{inj}^3}\left(\frac{p}{p_{inj}}\right)^{-s} + s\int_{p_0}^{p}\frac{dp'}{p'}\left(\frac{p'}{p}\right)^{s} g(p')$$

MORE EFFECTIVE FOR STEEP SECONDARIES (B!)

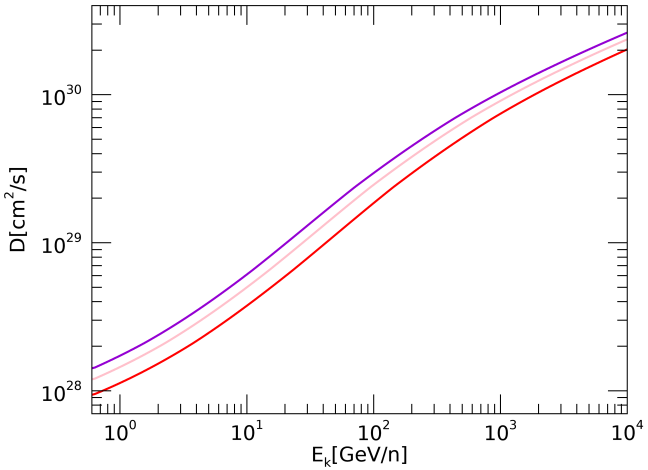
GRAMMAGE ACCUMULATED WITHIN THE SOURCE

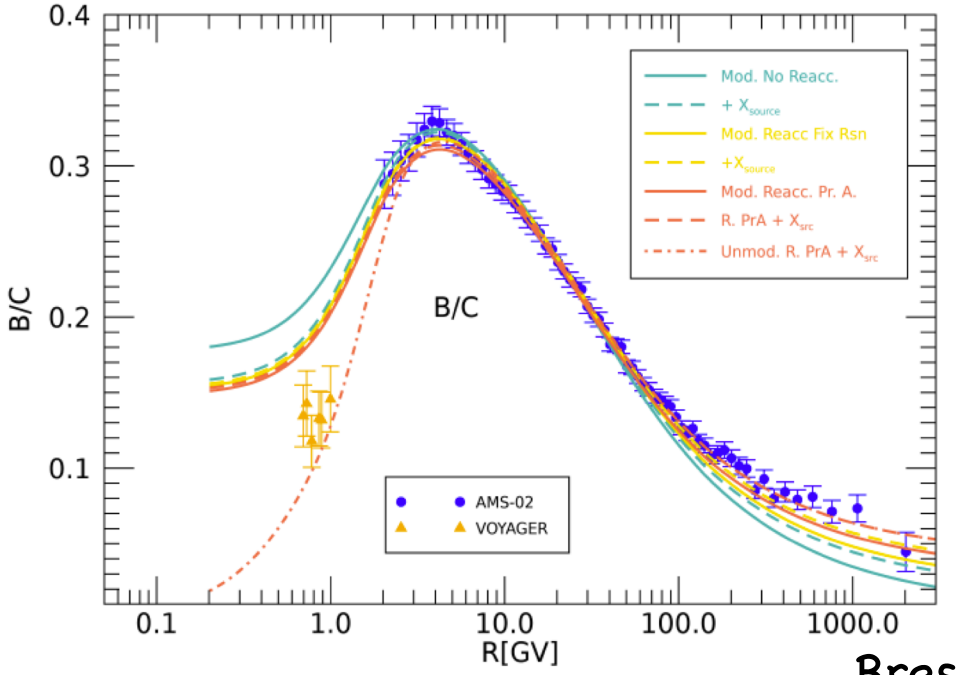
FLATTENING OF SECONDARIES AT HIGH ENERGY

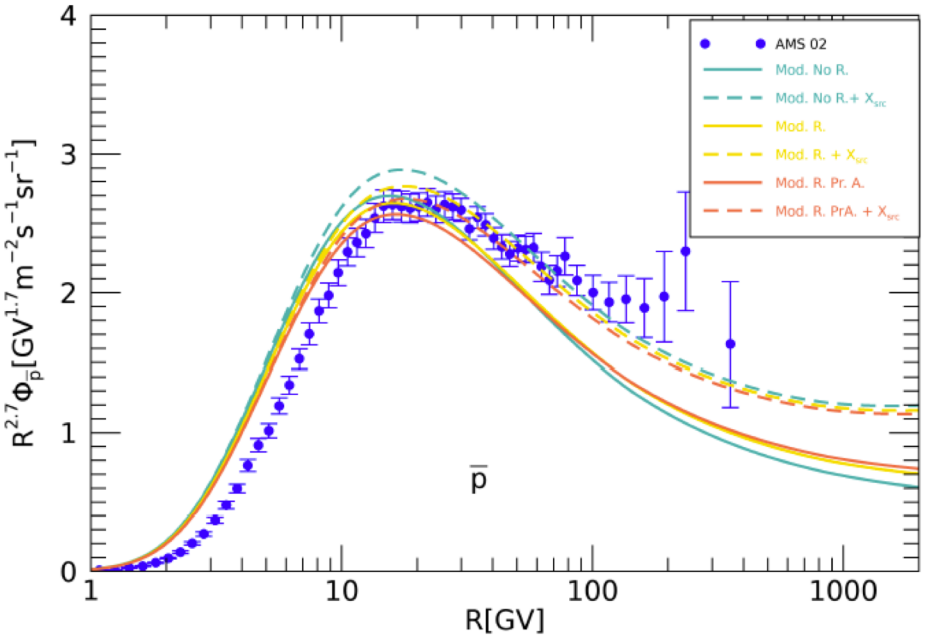
$$X_{\rm SNR} \approx 1.4 r_s m_p n_{\rm ISM} c T_{\rm SNR} \approx 0.17\,{\rm g\,cm^{-2}}\frac{n_{\rm ISM}}{\rm cm^{-3}}\frac{T_{\rm SNR}}{2\times10^4{\rm yr}},$$

MORE EFFECTIVE FOR SMALLER GRAMMAGE: ANTI-P

SELF GENERATED WAVES +REACCELERATION +SOURCE GRAMMAGE







Bresci + in prep

SUMMARY

- RECENT FINDINGS BY PAMELA AND AMS-02:
  - BREAKS IN THE SPECTRA OF PRIMARIES
  - B/C *A LA KOLMOGOROV*
  - FLAT ANTI-PROTONS
  - RISING POSITRON FRACTION

- CHALLENGE TO STANDARD SCENARIO OF CR ORIGIN AND PROPAGATION?

- SO FAR ONLY SUGGEST THAT MORE PHYSICAL PROCESSES NEED TO BE TAKEN INTO ACCOUNT IN THE DESCRIPTION OF PROPAGATION, INCLUDING THE ROLE OF NON-LINEARITIES IN PROPAGATION: A VIEW ALREADY ACCEPTED FOR ACCELERATION