ON THE ORIGIN OF GALACTIC COSMIC RAYS

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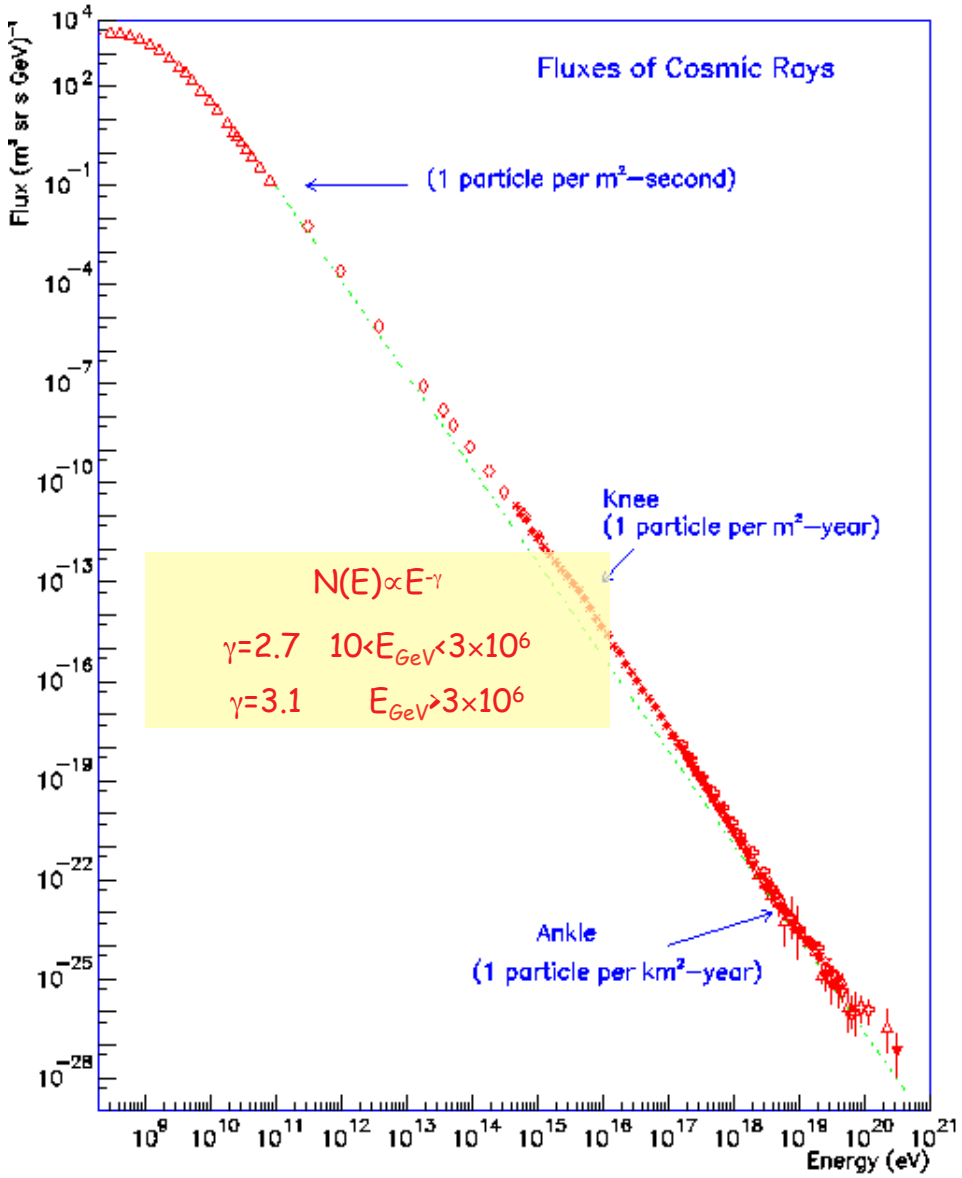
COSMIC RAYS

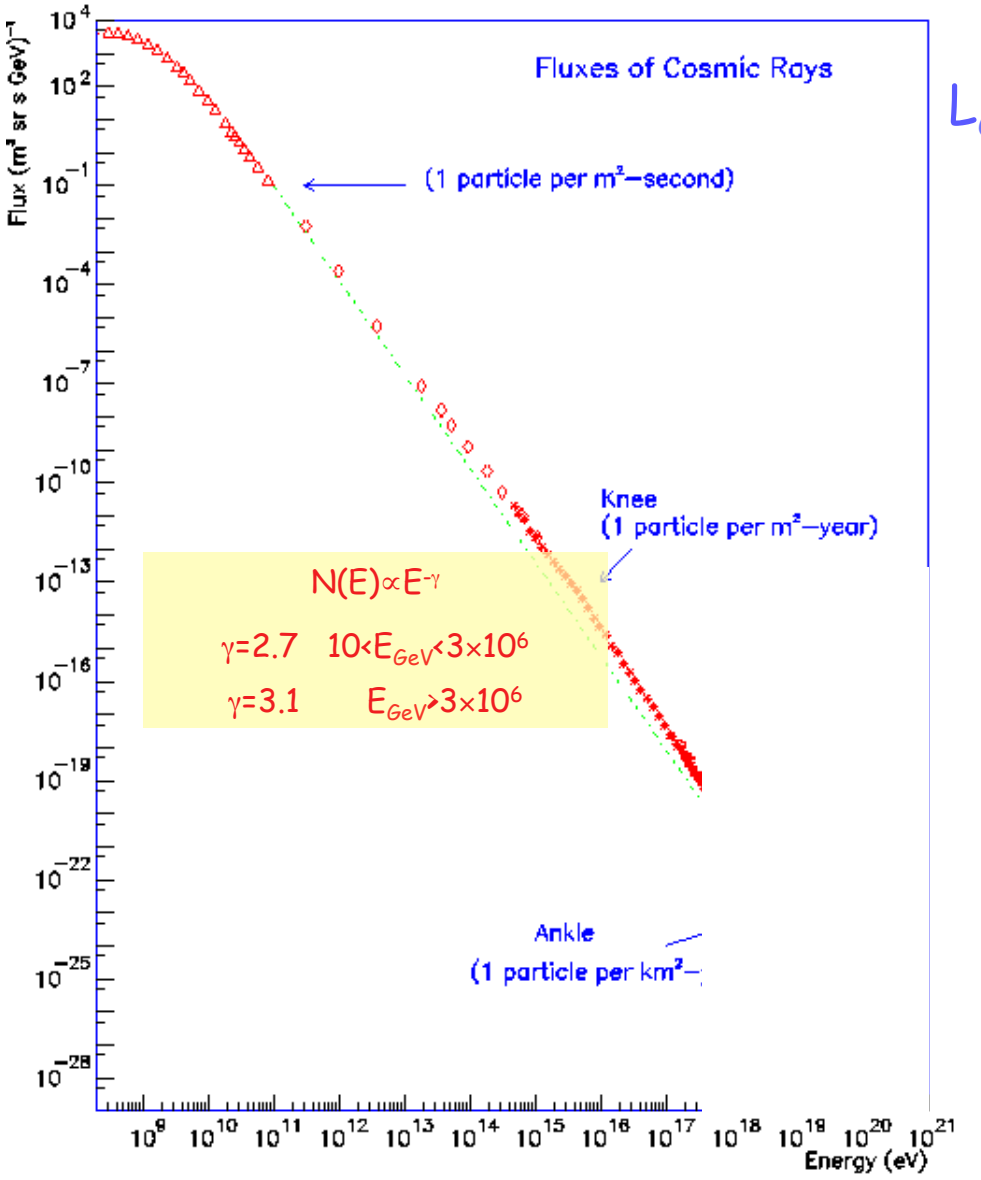


- 98% OF PARTICLES ARE PROTONS AND NUCLEI
  - 87% PROTONS
  - 12% He
  - 1% HEAVIER NUCLEI
- 2% ARE ELECTRONS
- ABOUT 10^{-3} ARE ANTIMATTER PARTICLES (e^+ AND anti-p)

FOR A LONG TIME KNEE AND ANKLE WERE THE ONLY SPECTRAL FEATURES

KNEE IDENTIFIED AS THE END OF THE GALACTIC PROTON SPECTRUM

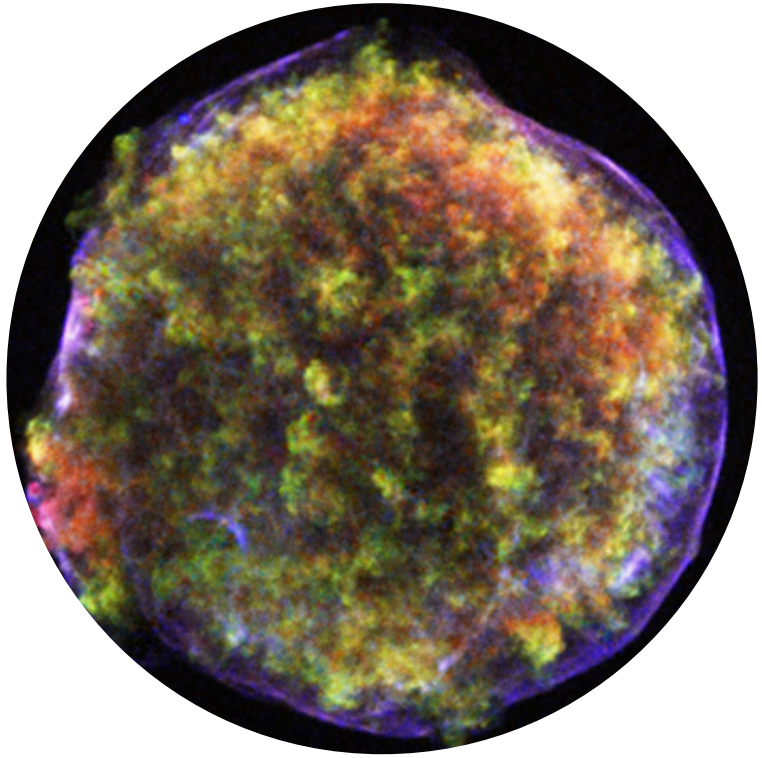
GALACTIC COSMIC RAYS



ASSOCIATION WITH Sne

(Baade & Zwicky 34)

$L_{CR} \sim 3 \times 10^{40}$ erg $s^{-1} \sim 10\% (10^{51}$erg/100yr)



ACCELERATION PROCESS:

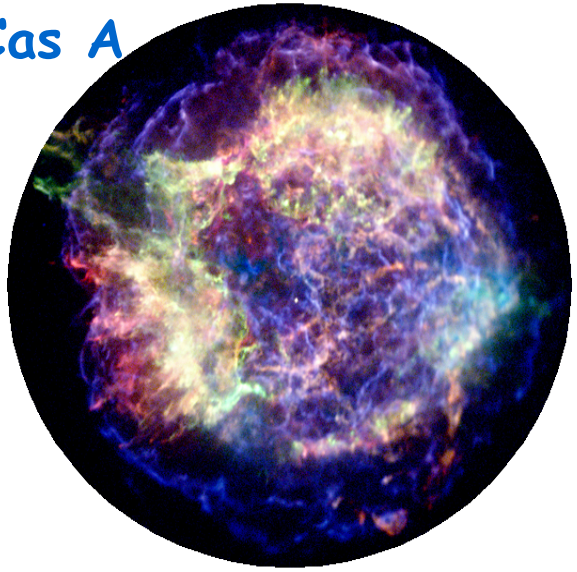
DIFFUSIVE SHOCK ACCELERATION

(Krymskii 77, Bell 78)

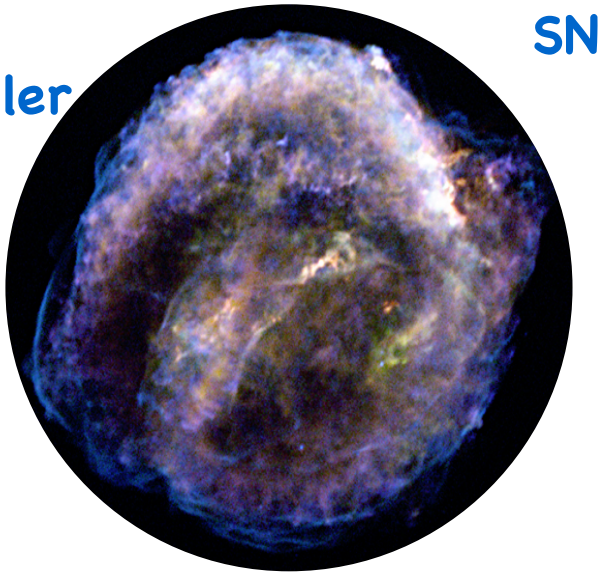
SUPPORTING EVIDENCE

RELATIVISTIC ELECTRONS IN SNRs (Ballet 06, Vink 12)

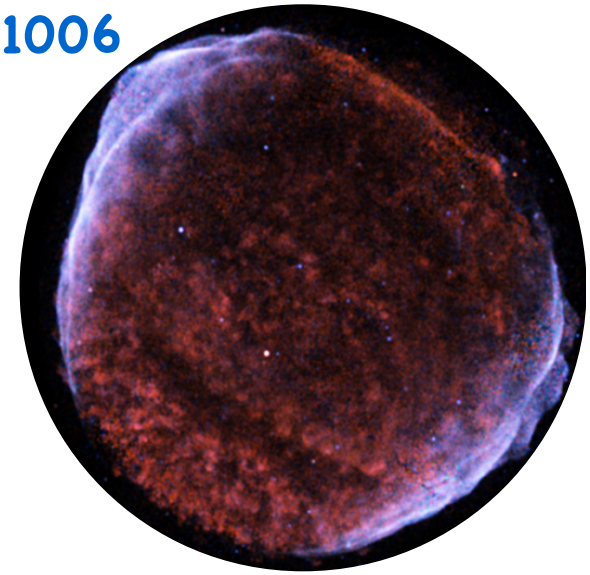
Cas A



Kepler



SN1006

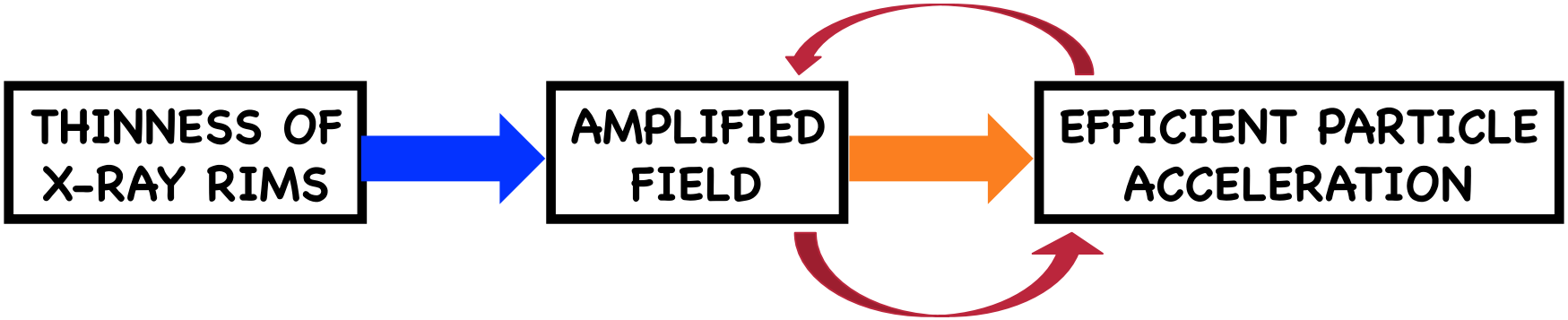


VIRTUALLY ALL YOUNG REMNANTS SHOW X-RAY SYNCHROTRON FILAMENTS

LOSS LENGTH $\Delta x = \sqrt{D\tau_{\rm sync}} = 0.04 B_{100}^{-3/2} pc$ ⇒ **AMPLIFIED MAGNETIC FIELD**

INDIRECT EVIDENCE FOR EFFICIENT CR ACCELERATION ⇐

IN THE SIMPLEST PICTURE



CAVEATS:

- **DAMPING MAY BREAK FIRST IMPLICATION**

  ALTHOUGH HIGH FIELDS ARE USUALLY REQUIRED EVEN WHEN DAMPING FITS BETTER THAN LOSSES (e.g. Rettig & Pohl 12, Ressler+ 14, Tran+ 15)

- **OTHER SOURCES OF AMPLIFIED FIELDS MAY BREAK SECOND**

  (e.g. Giacalone & Jokipi 07, Beresniak+ 09)

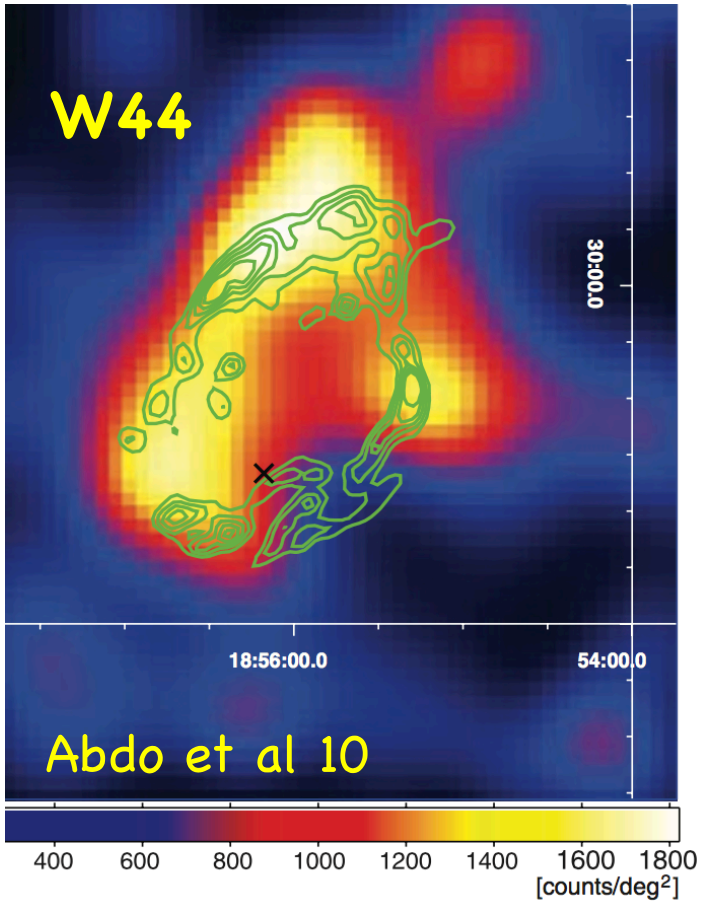
- **AMPLIFIED FIELDS ARE NOT BOUND TO GUARANTEE EFFICIENT SCATTERING AND REACHING HIGH ENERGIES**

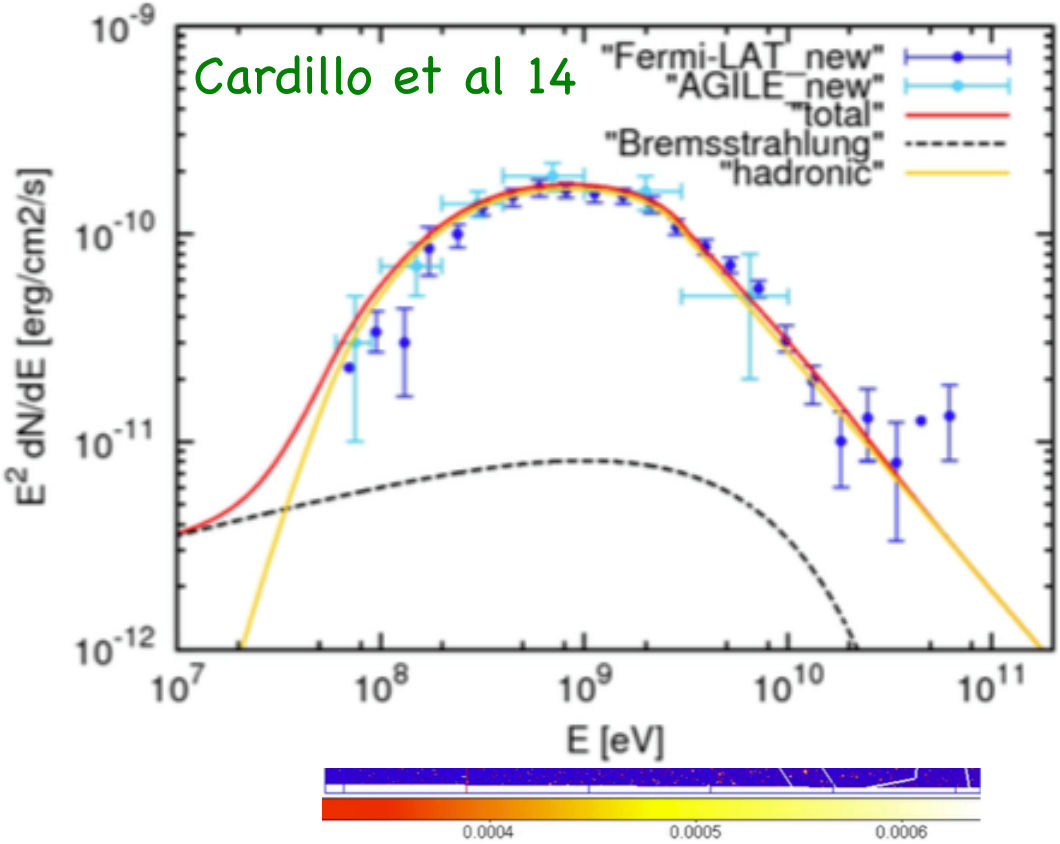
  INITIAL CONCERN ABOUT NON-RESONANT STREAMING INSTABILITY (Bell 04), SO FAR MOST VALUED MFA PROCESS...

DIRECT EVIDENCE?

RELATIVISTIC PROTONS IN MIDDLE AGED SNRs INTERACTING WITH MOLECULAR CLOUDS

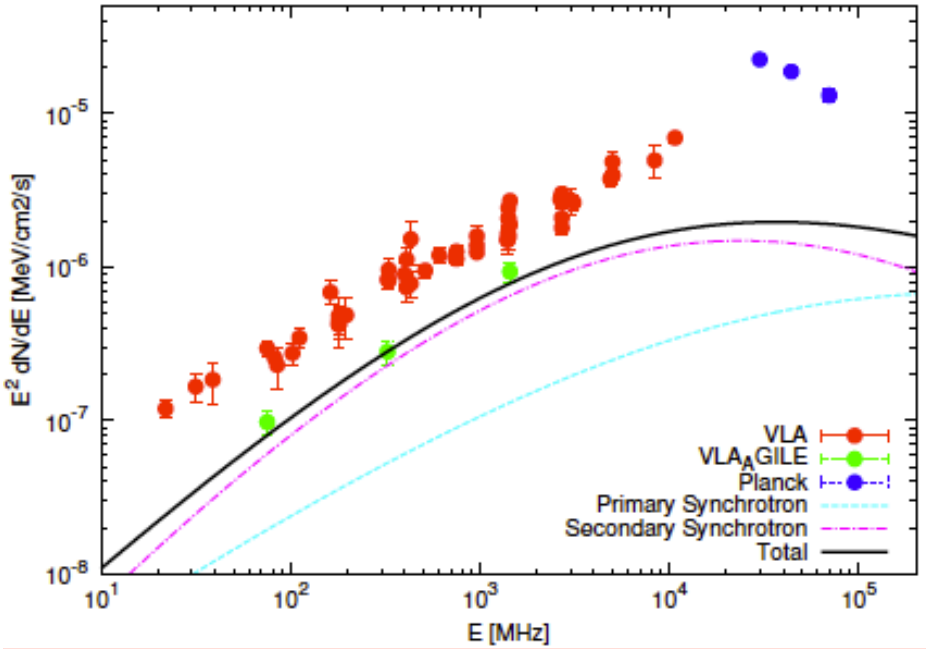
(AGILE: Giuliani+ 11, Cardillo+ 14; FERMI: Abdo+ 10, Ackermann+ 11)





AT A CLOSER LOOK: MOSTLY COMPRESSION AND REACCELERATION OF GALACTIC CRs (Uchyiama+ 10; Lee+ 15; Cardillo, EA, Blasi 16).

W44: MOSTLY REACCELERATION



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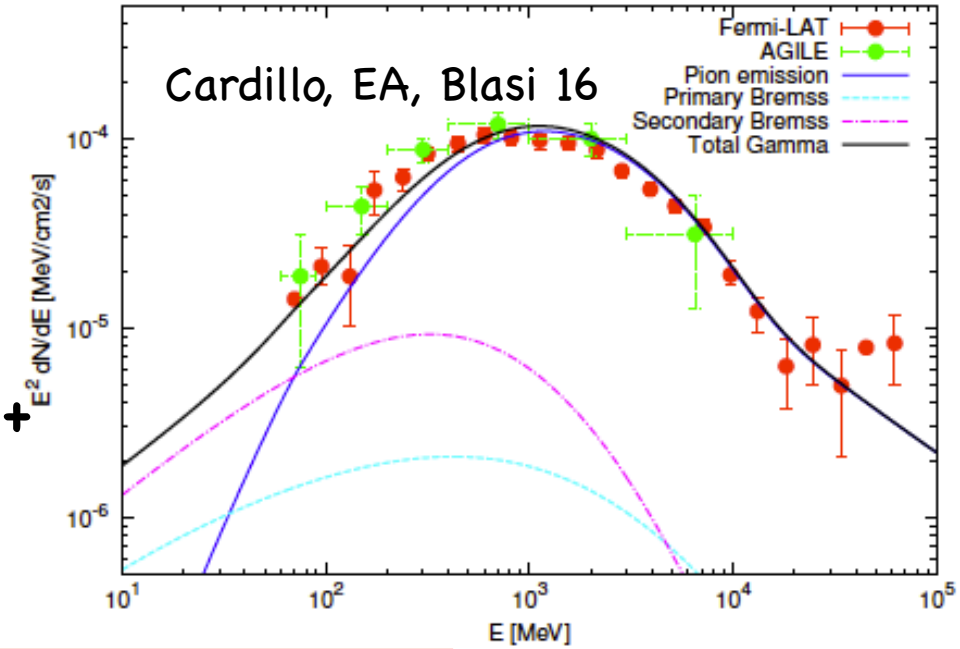
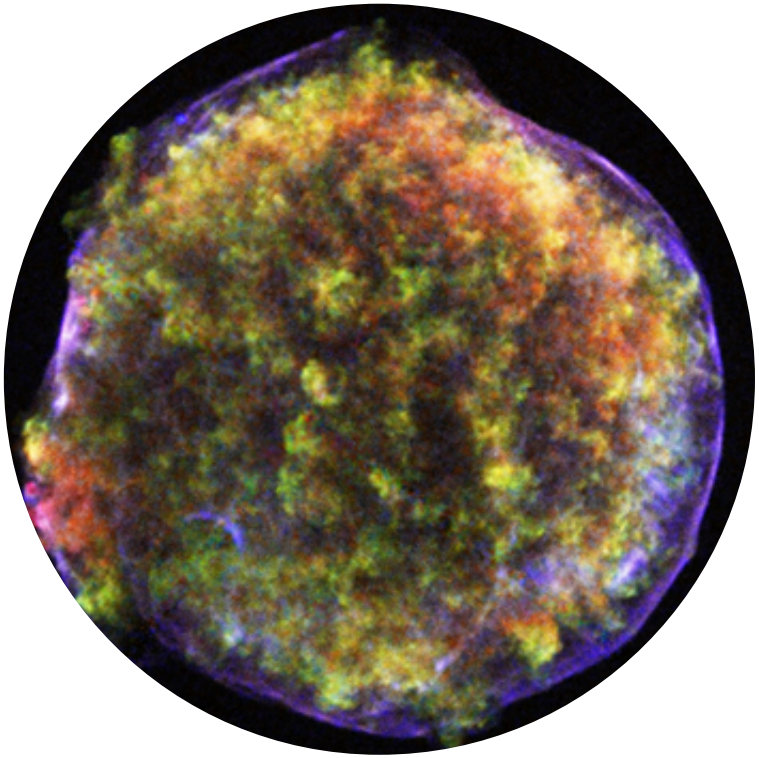


$$p_{\rm MAX} = 20{\rm GeV/c}\left(\frac{B_0}{3\mu G}\right)\left(\frac{t_{\rm int}}{2\times10^4{\rm yr}}\right)\left(\frac{L_c}{0.1pc}\right)^{-1}\left(\frac{v_S}{100{\rm km/s}}\right)^4$$

$\xi_{CR} \approx 2 \times 10^{-5}$

- OLD, SLOW SHOCK, LOW EFFICIENCY
- BRIGHT THANKS TO WEALTH OF TARGET

LOOK FOR EFFICIENT ACCELERATION ELSEWHERE,
e.g. TYCHO (Morlino&Caprioli 12)

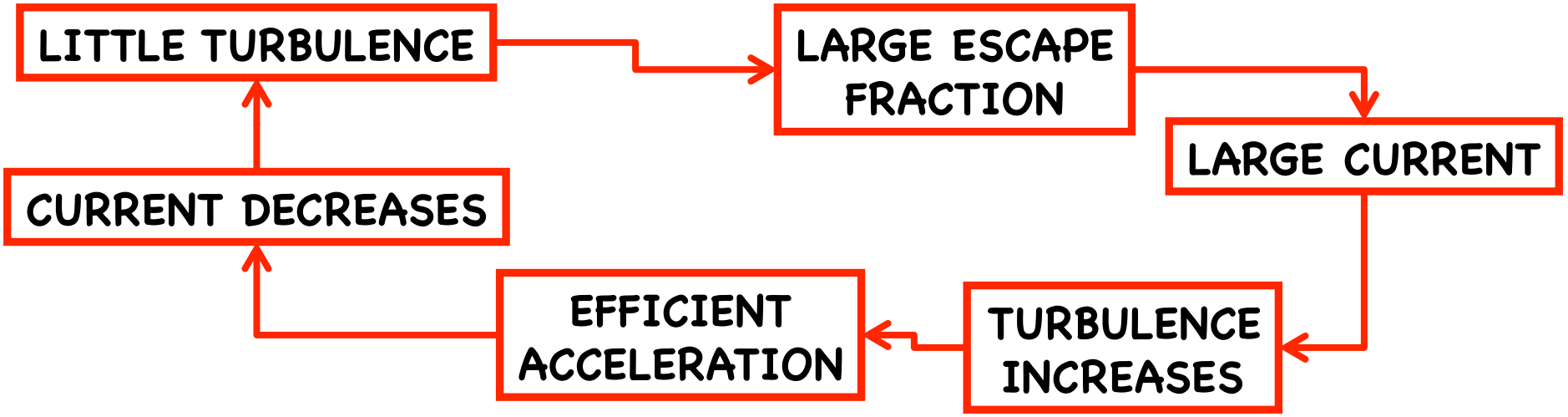


YOUNG SNRs

NON-RESONANT MFA (Bell 04) CAN ENSURE HIGH P_{MAX} BUT FOR A SHORT TIME (<FEW X 100 YR)

- MFA DUE TO CURRENT OF ESCAPING PARTICLES
- GROWTH RATE PROPTO J_{CR} WHICH DEPENDS ON SPECTRUM AT THE SHOCK, P_{MAX} AND V_S

SELF-REGULATION MECHANISM



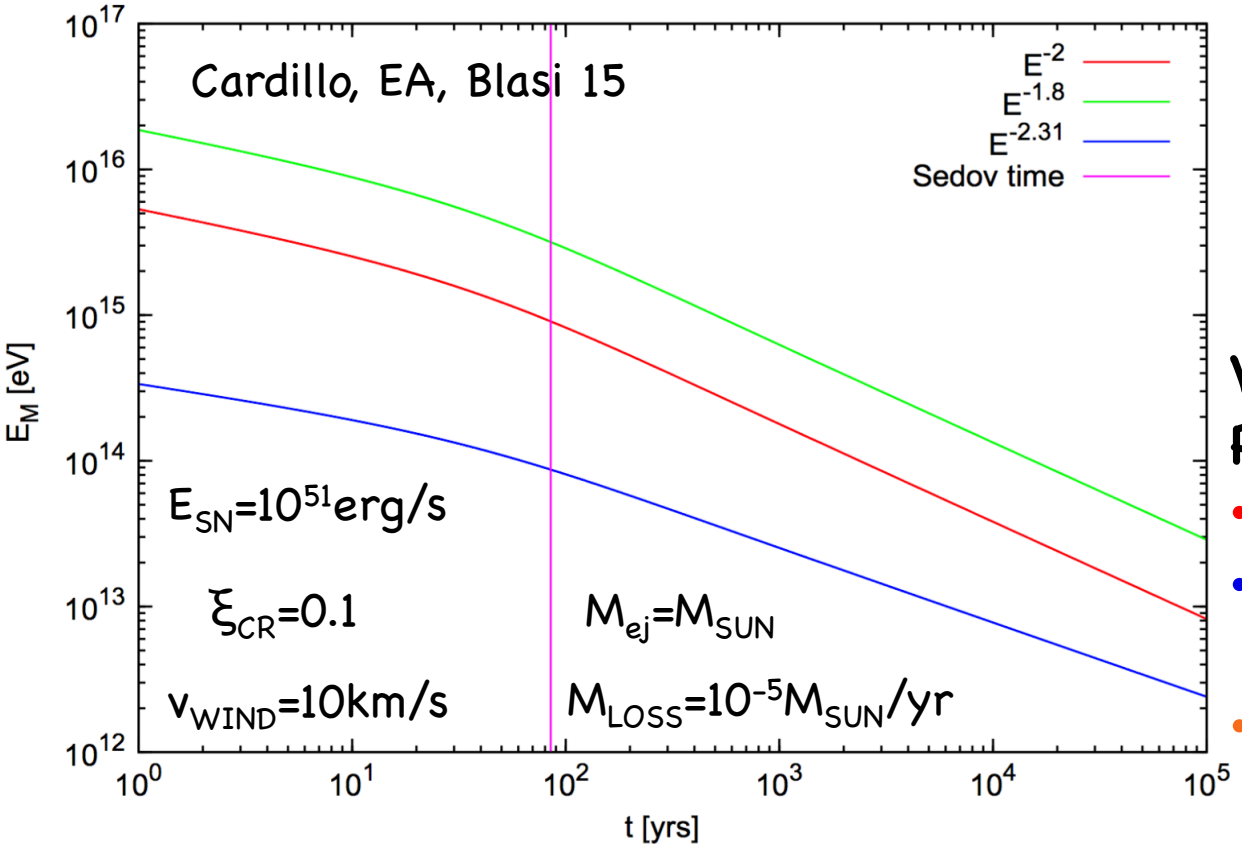
PEVATRONS

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

Γ_{CR} >2 IF Γ_{SRC} >2

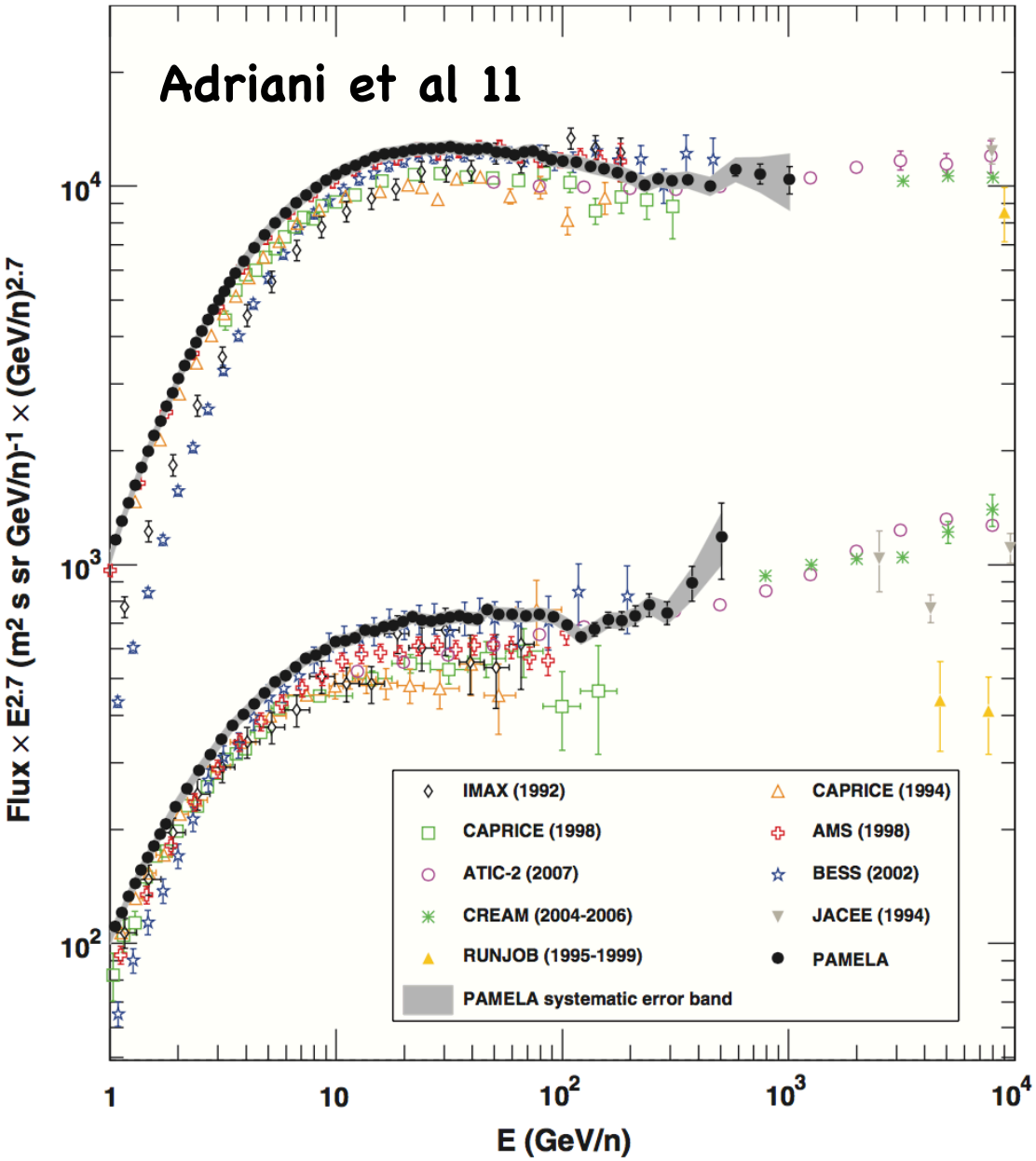
Γ_{CR} =2 IF Γ_{SRC} ≤2

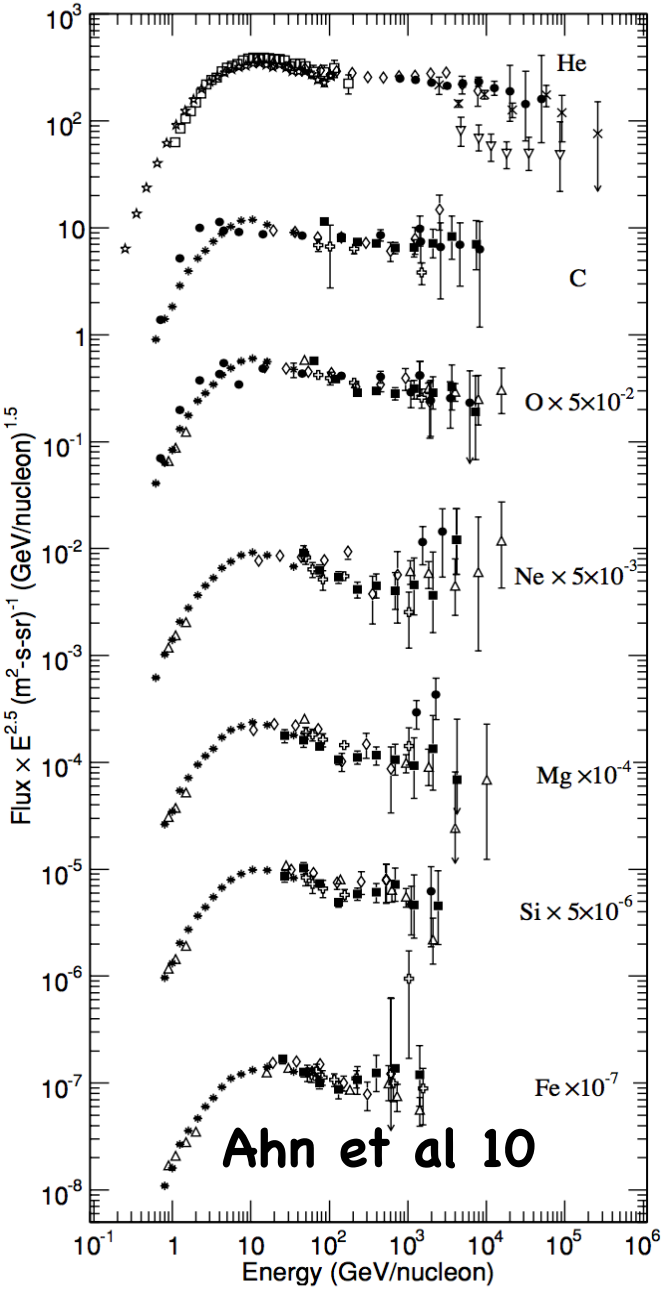
WITH Γ_{CR} >2, P_{max}=PeV REQUIRES:

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

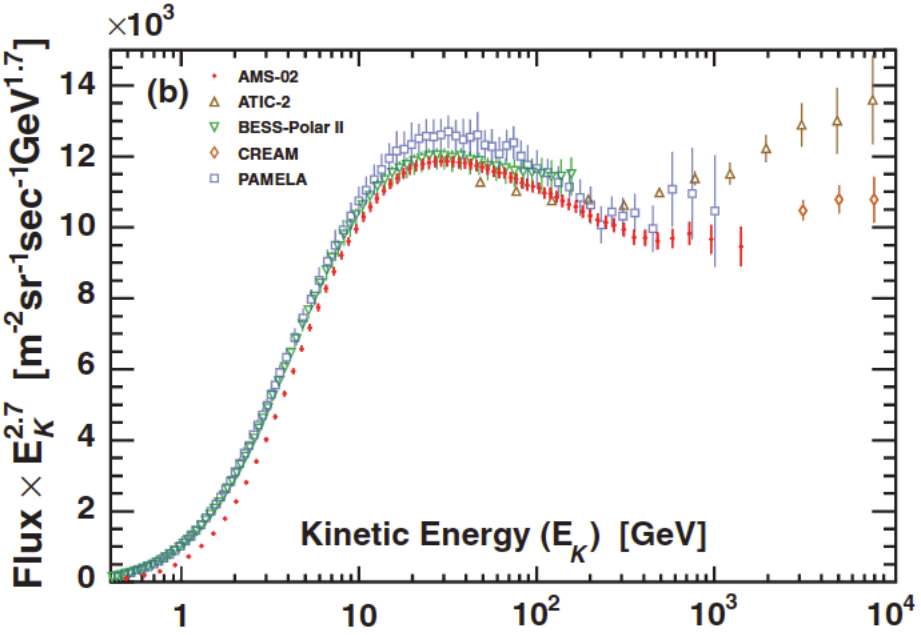
NEWS ABOUT INJECTION AND PROPAGATION

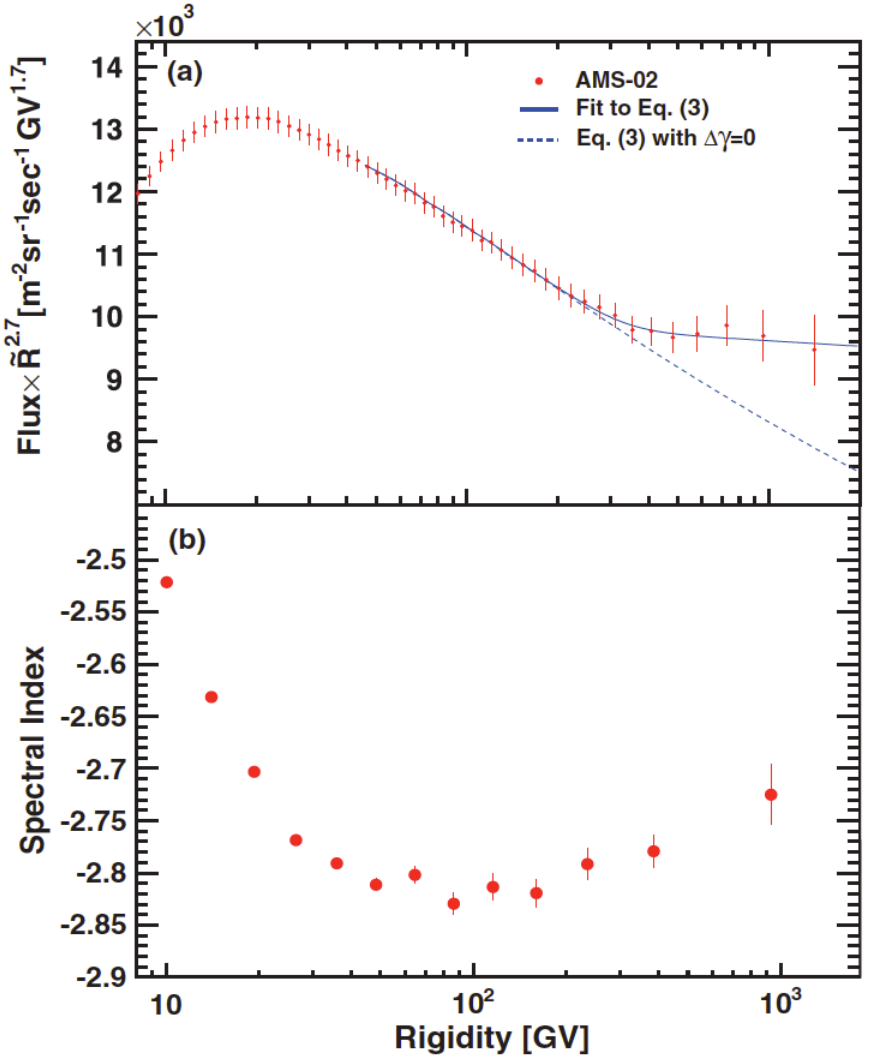
SPECTRAL BREAKS





AMS02 CONFIRMS





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

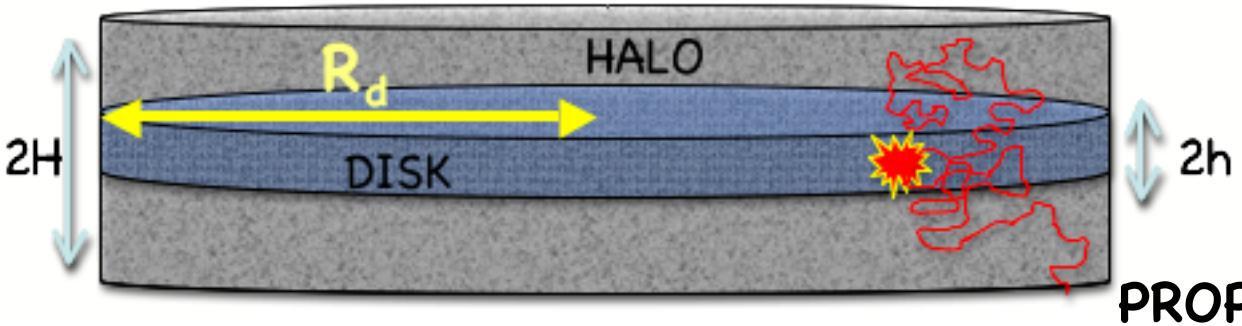
$\gamma = -2.849$ $\Delta\gamma = 0.133$

$R_0 = 336\ GV$

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

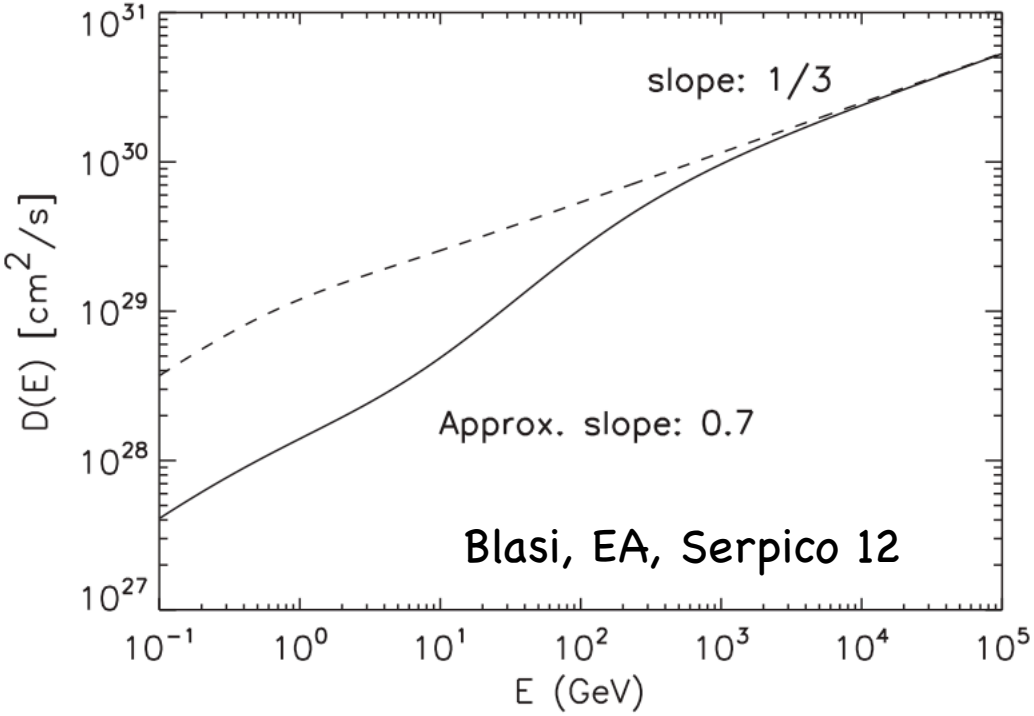
PROTON SPECTRUM $N_{\rm p}(E) = \dfrac{N_S(E)\mathcal{R}}{2\pi R_d^2 H}\tau_{\rm esc} \propto E^{-\gamma_{\rm inj}-\delta_{\rm e}}$

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)

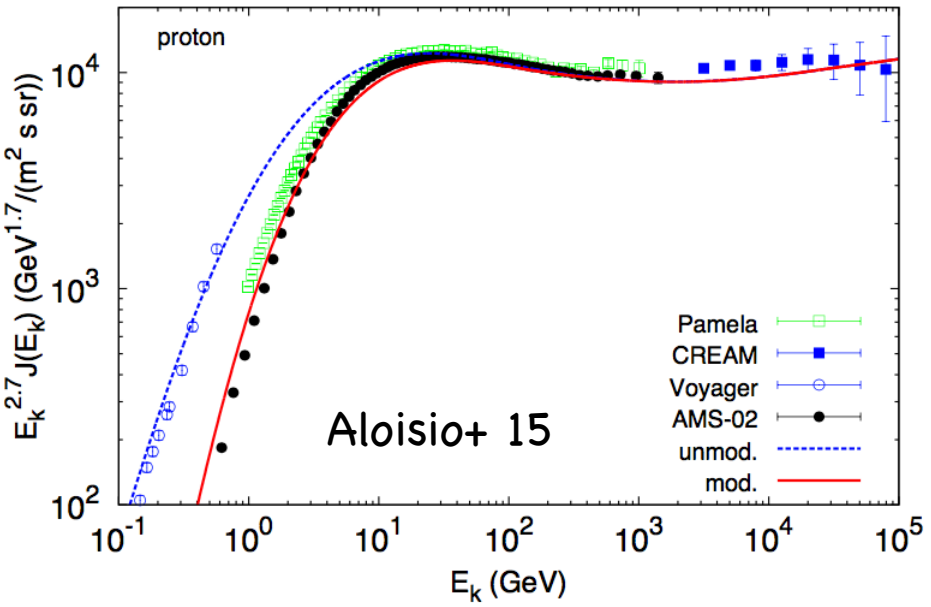
UP TO WHAT SCALE/ENERGY SELF-GENERATED WAVES ARE DOMINANT?

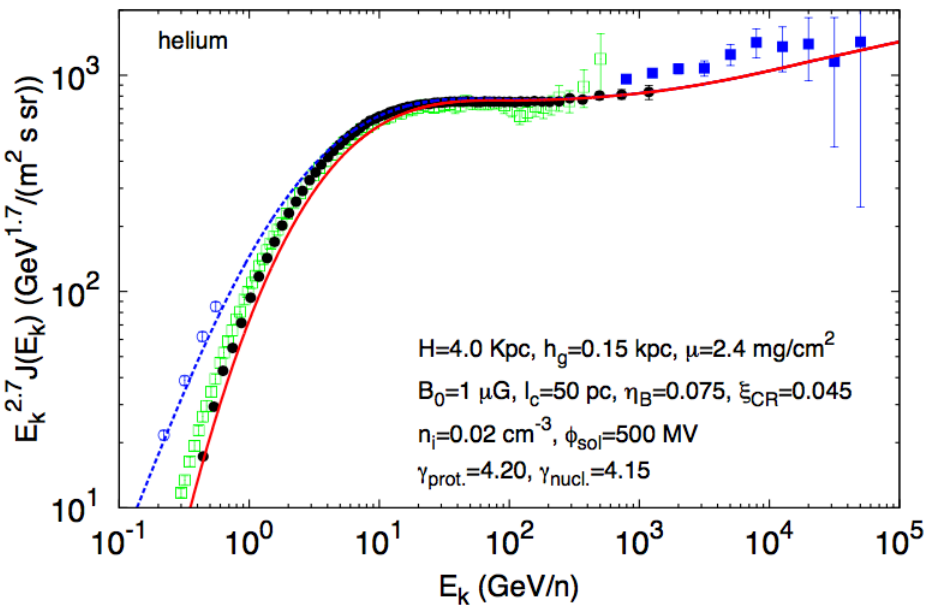


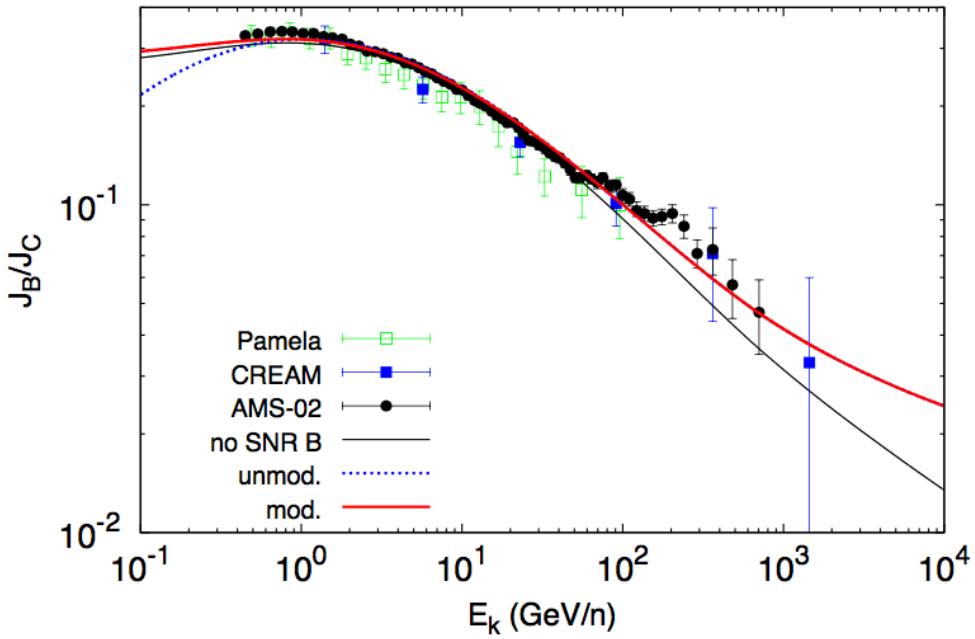
$$W_{ext}(k_{TR}) = W_{CR}(k_{TR}) \qquad k_{TR}\, r_L(E_{TR}) = 1$$

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

TAKING ALL INTO ACCOUNT..





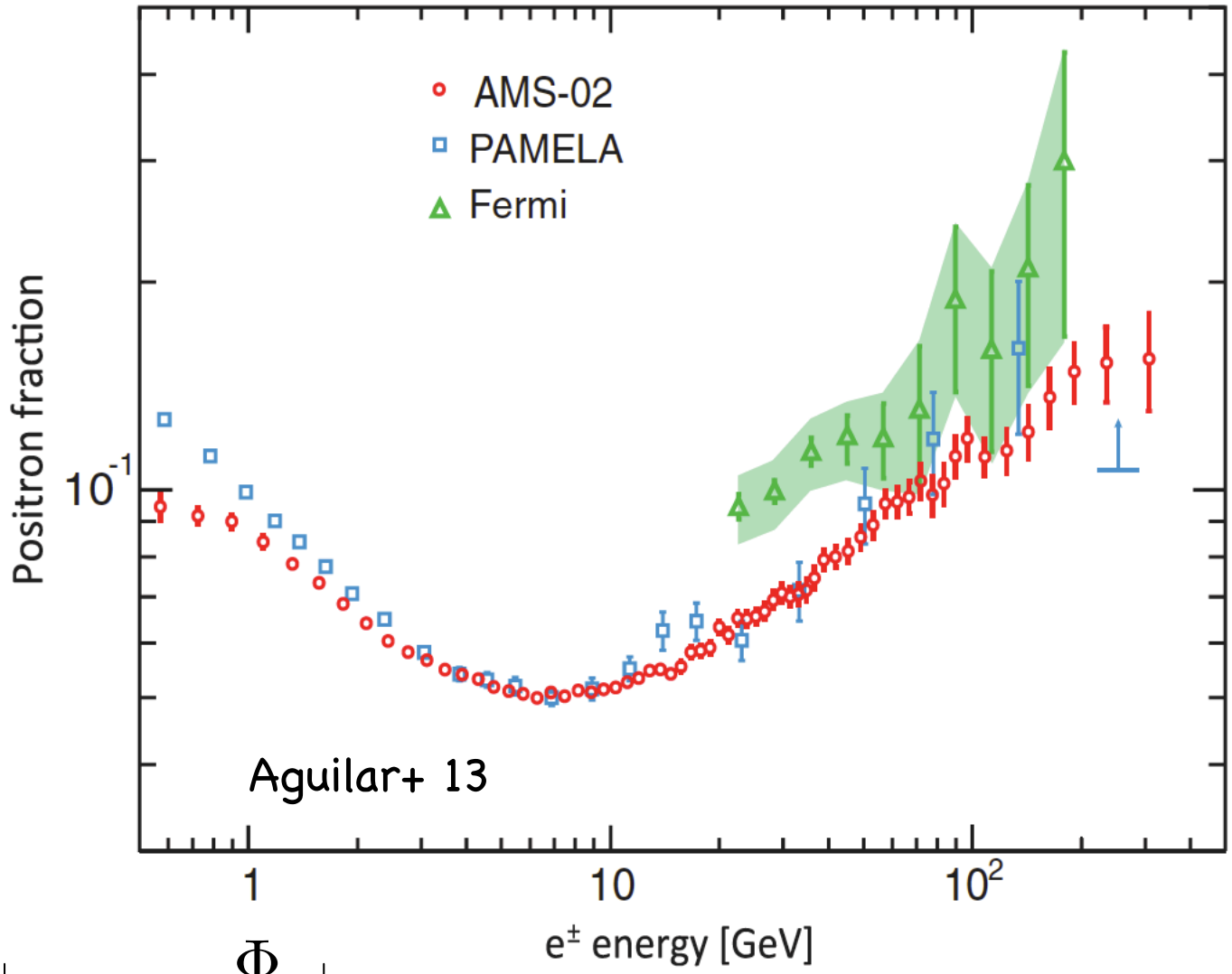


IMPLICATION:

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

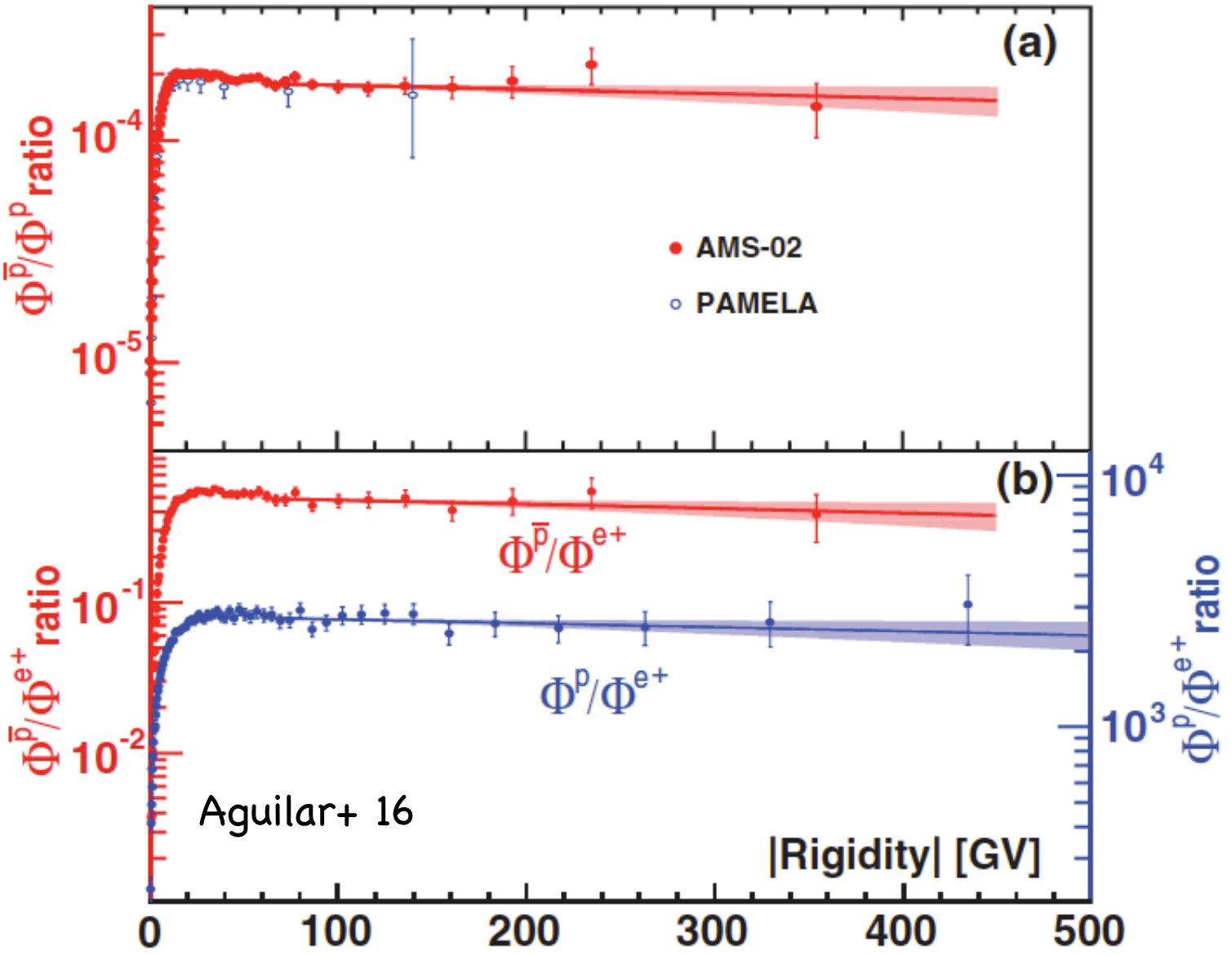
- ✓ OK WITH AMS-02 B/C
- ✓ GOOD FOR ANISOTROPY (e.g. Blasi&EA 12)
- X BAD FOR MAX. EN. IN SNRs

ODDITIES OF ANTIMATTER



$$\frac{\Phi_{e+}}{\Phi_{e+}+\Phi_{e-}} \approx \frac{\Phi_{e+}}{\Phi_{e-}}$$

ODDITIES OF ANTIMATTER



SECONDARIES VS PRIMARIES: EXPECTATION

SPECTRUM OF PRIMARIES

$$N_{\rm prim}(E) = \frac{N_S(E)\mathcal{R}}{2\pi R_d^2 H}\tau_{\rm esc}$$

SPECTRUM OF STABLE SECONDARIES

$$N_{\rm sec}(E) \approx N_{\rm prim}(E) c n_H \sigma_{\rm sp} \tau_{\rm esc} \propto N_{\rm prim}\tau_{\rm esc}$$

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

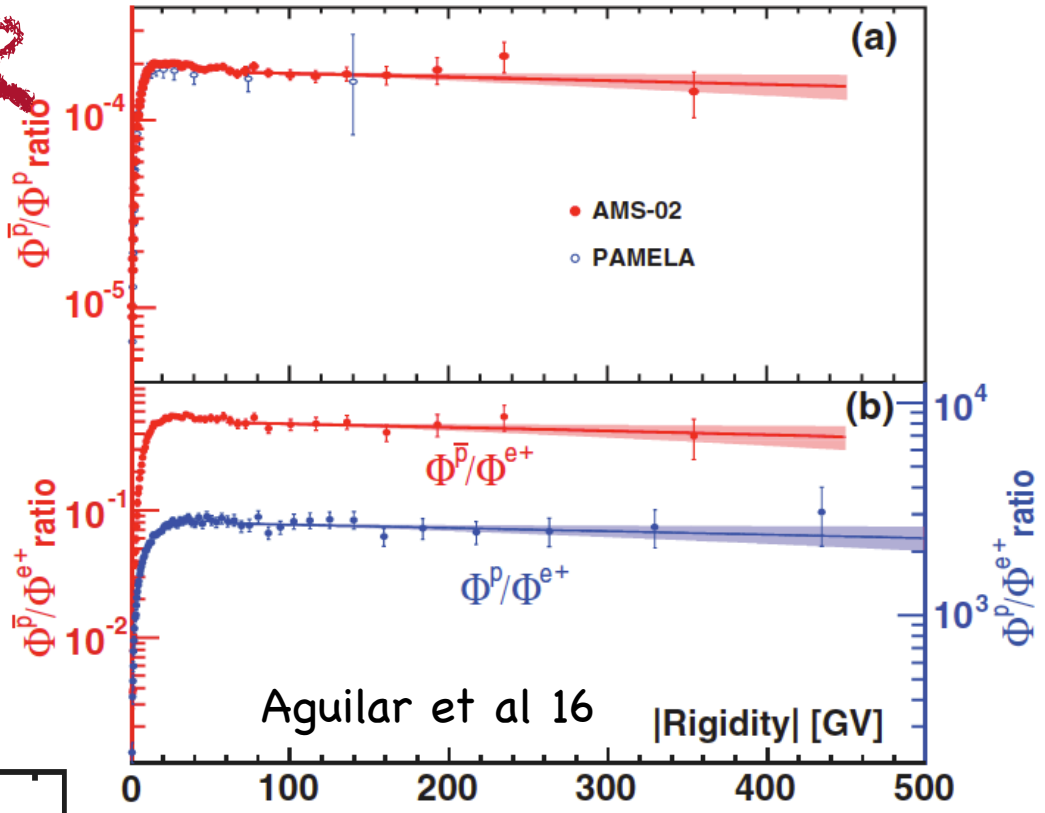
ANALOGOUSLY

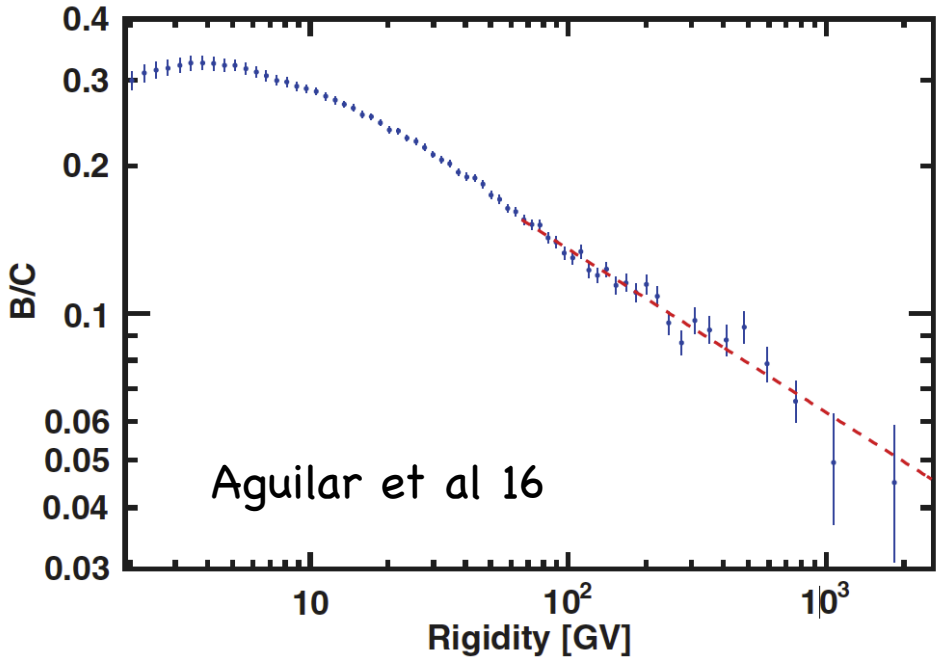
$$\frac{\Phi_{\bar{p}}(E)}{\Phi_p(E)} \propto E^{-\delta_e}$$

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

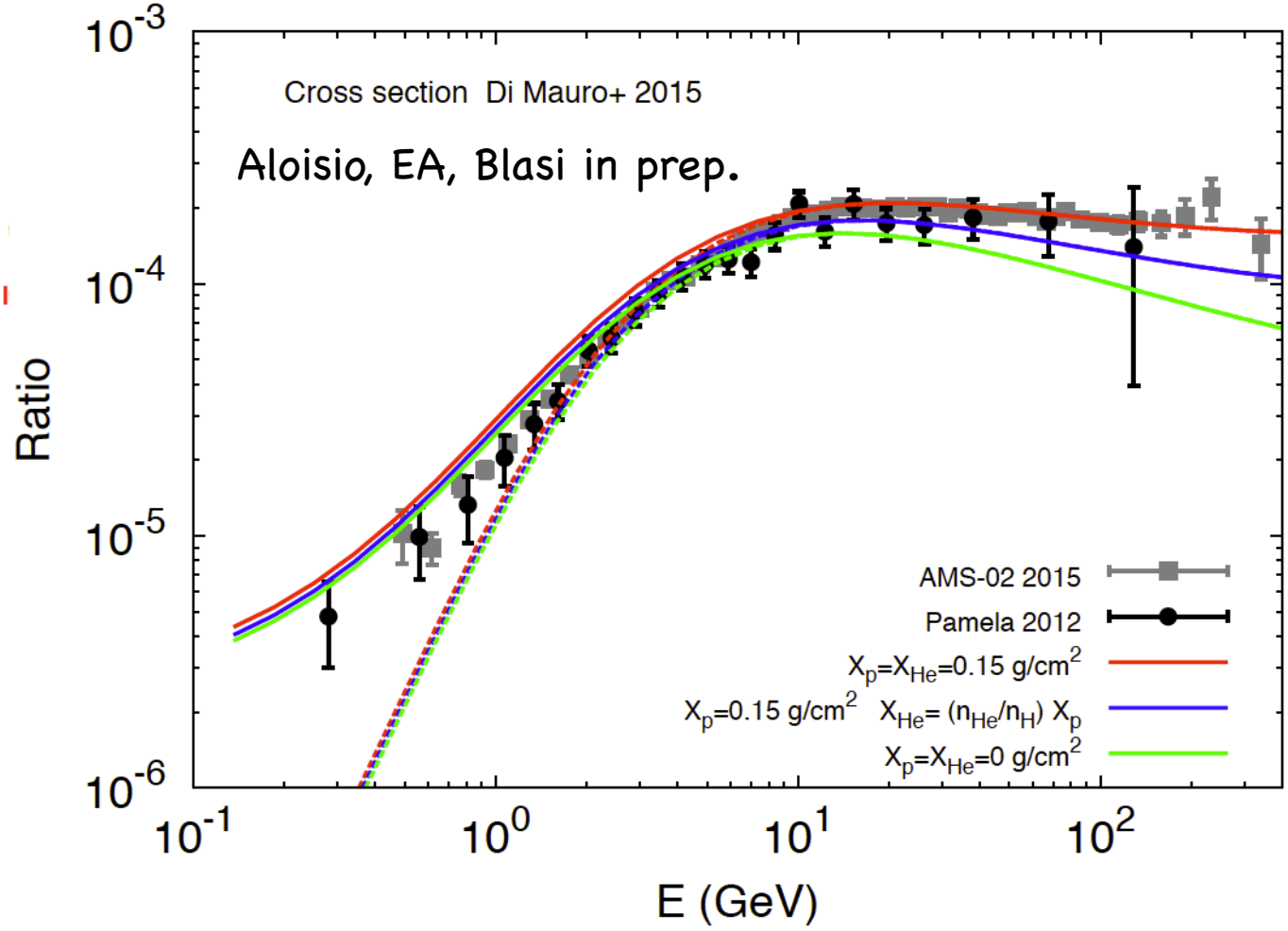




B/C IS WELL BEHAVED: DECREASES WITH ENERGY

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

ANTI-PROTONS

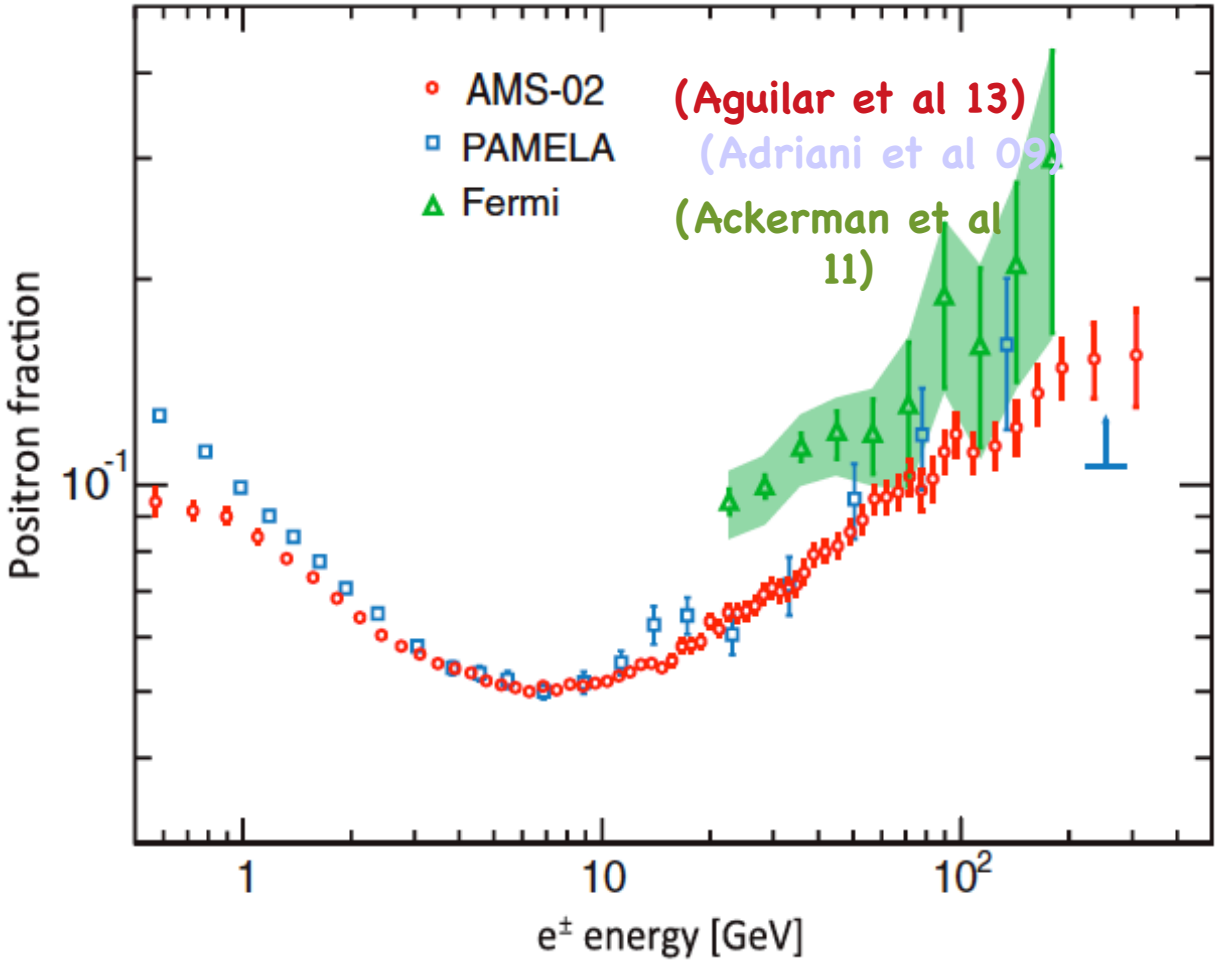


PRODUCTION CROSS-SECTION: INCREASES WITH ENERGY AND LARGE UNCERTAINTIES (Di Mauro+ 16)

- FLAT DIFFUSION COEFFICIENT
- FLATTENING OF THE PARENT P SPECTRA

NOT A REAL ISSUE

THE POSITRON "EXCESS"



MANY MANY IDEAS (& PAPERS):

- DARK MATTER
- NEW CR PROPAGATION SCENARIOS
- ASTROPHYSICAL SOURCES

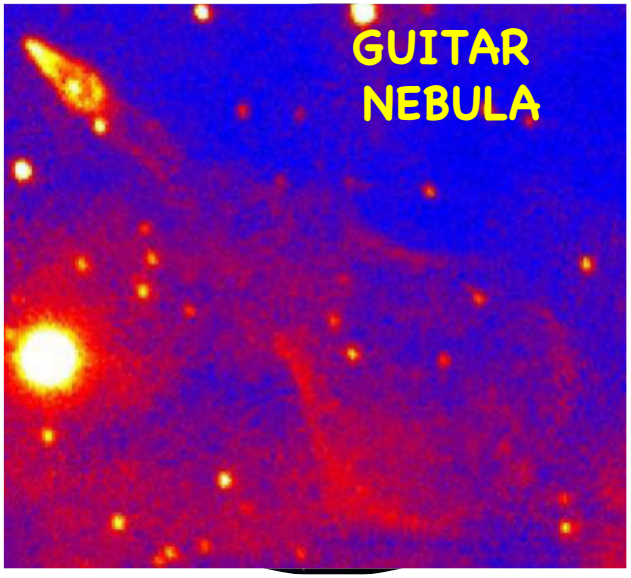
(e.g. Serpico 12, Di Mauro+ 17, EA & Blasi 17)

- e^+ ONLY SECONDARIES
- e^- SPECTRUM SAME AS p SPECTRUM

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

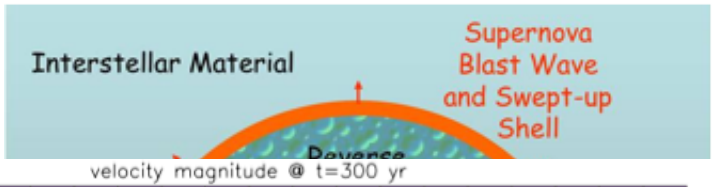
PULSARS AND THEIR NEBULAE

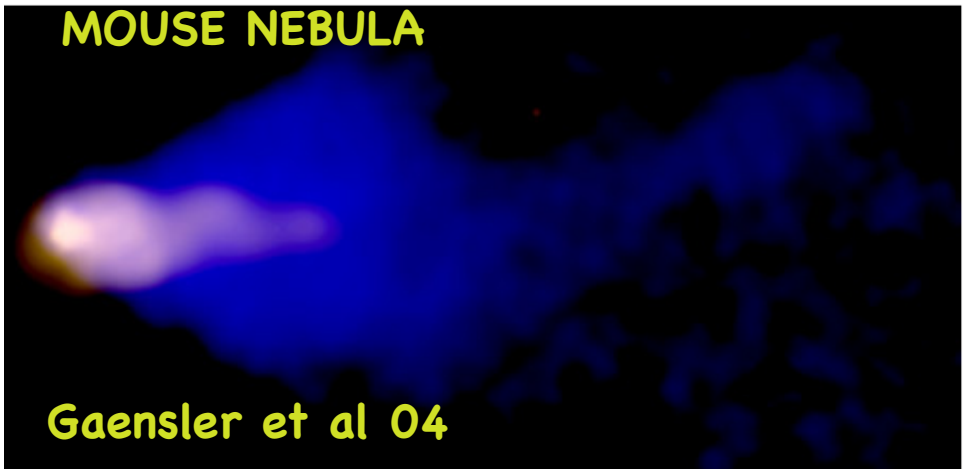
- **EXCELLENT FACTORIES OF LEPTONIC ANTIMATTER**
- **IMMEDIATELY SUGGESTED AS THE SOURCES OF e^+ EXCESS** (e.g. Hooper, Blasi, Serpico 08, Grasso+ 09, Heyl+ 10, Blasi & EA 11)

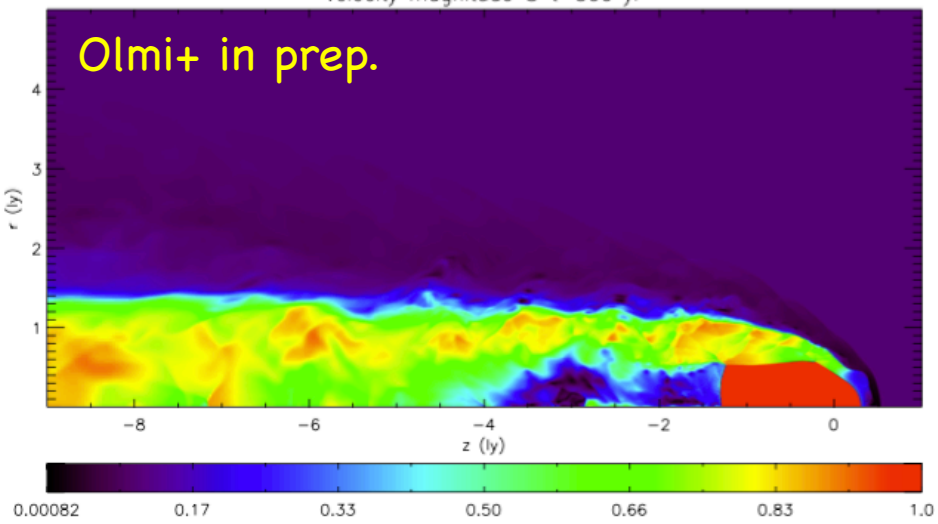


- **MOST ROTATIONAL ENERGY → PAIR WIND**
- **BUT WIND CONFINED BY PARENT SNR**
- **PARTICLES CAN ESCAPE ONLY AFTER PSR LEAVES SNR** (Bykov+ 17 for a recent review)

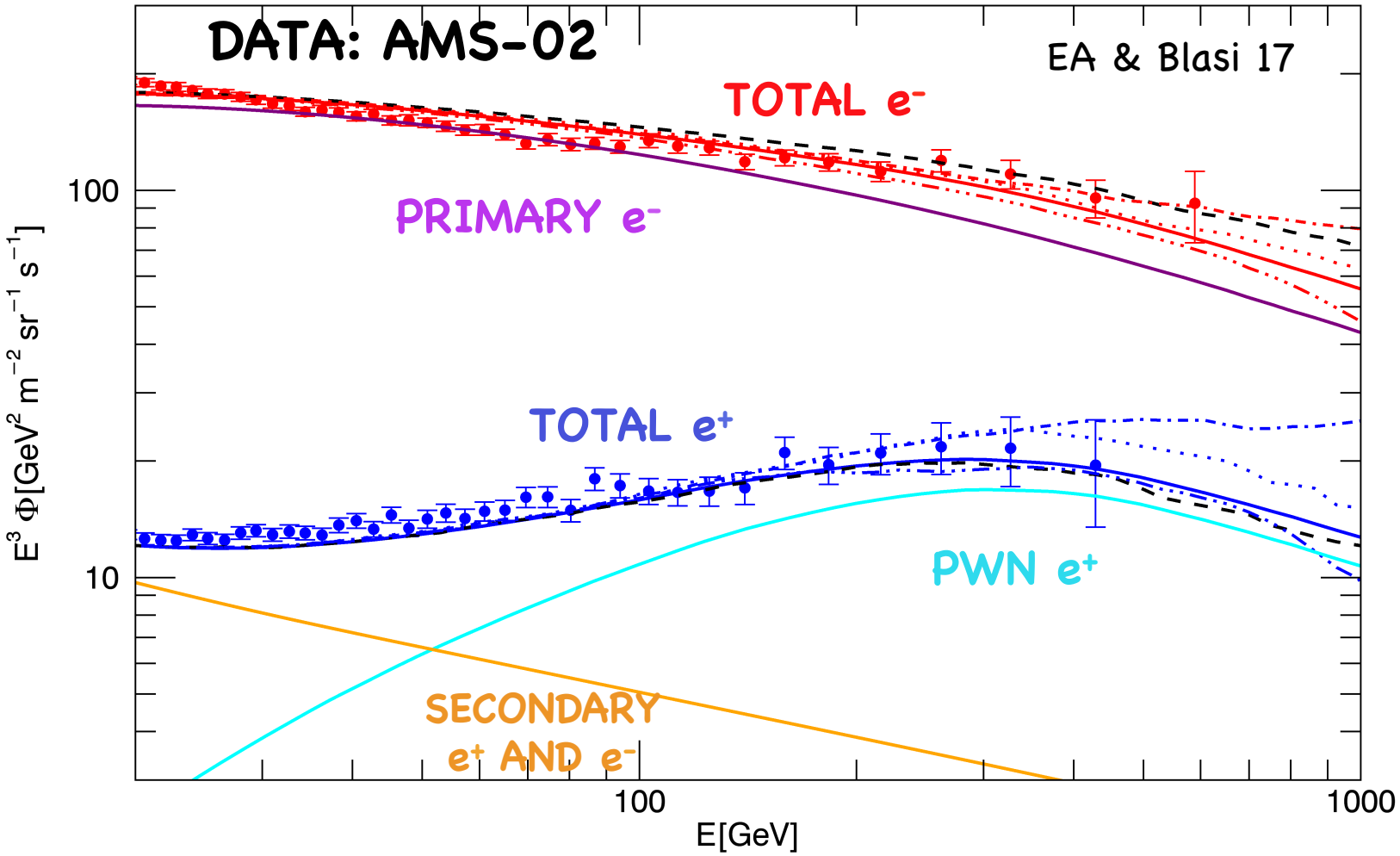
ESCAPING SPECTRUM?





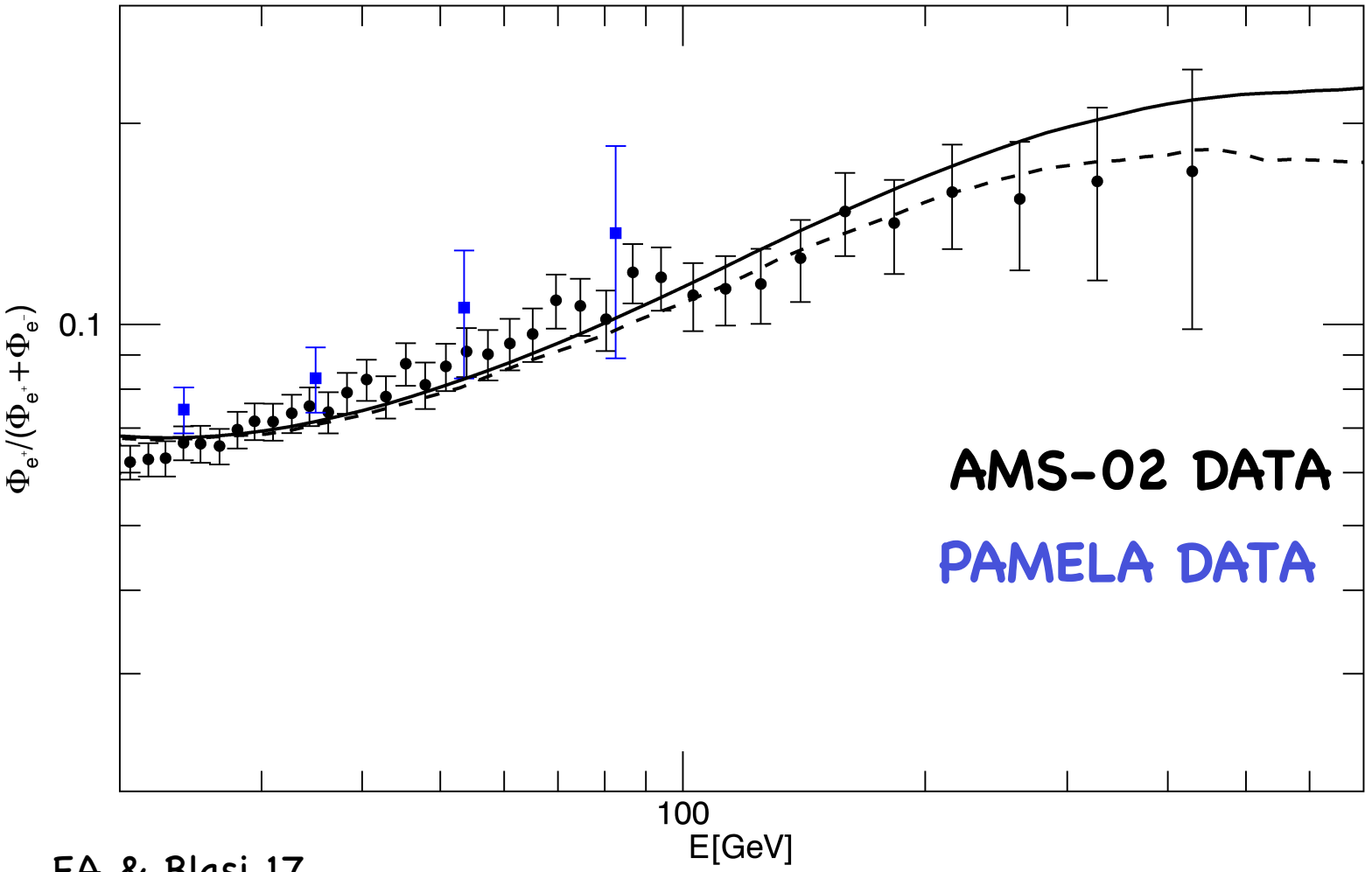


POSITRONS FROM PWNe



PWN ACCELERATION EFFICIENCY 12%
INJECTED SPECTRUM $E^{-1.5}$ E<500 GEV

POSITRON FRACTION



EA & Blasi 17

SUMMARY

- NO DIRECT PROOF OF CR ACCELERATION IN SNRs YET
- SHORT-LIVED, POSSIBLY RARE, PEVATRONS
- 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:
  - PWN LIKELY TO CONTRIBUTE SOME e^+
  - ROLE OF NON-LINEARITIES IN PROPAGATION: A VIEW ALREADY ACCEPTED FOR ACCELERATION