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A progress report on the origin of VHE Cosmic Rays

Pasquale Blasi

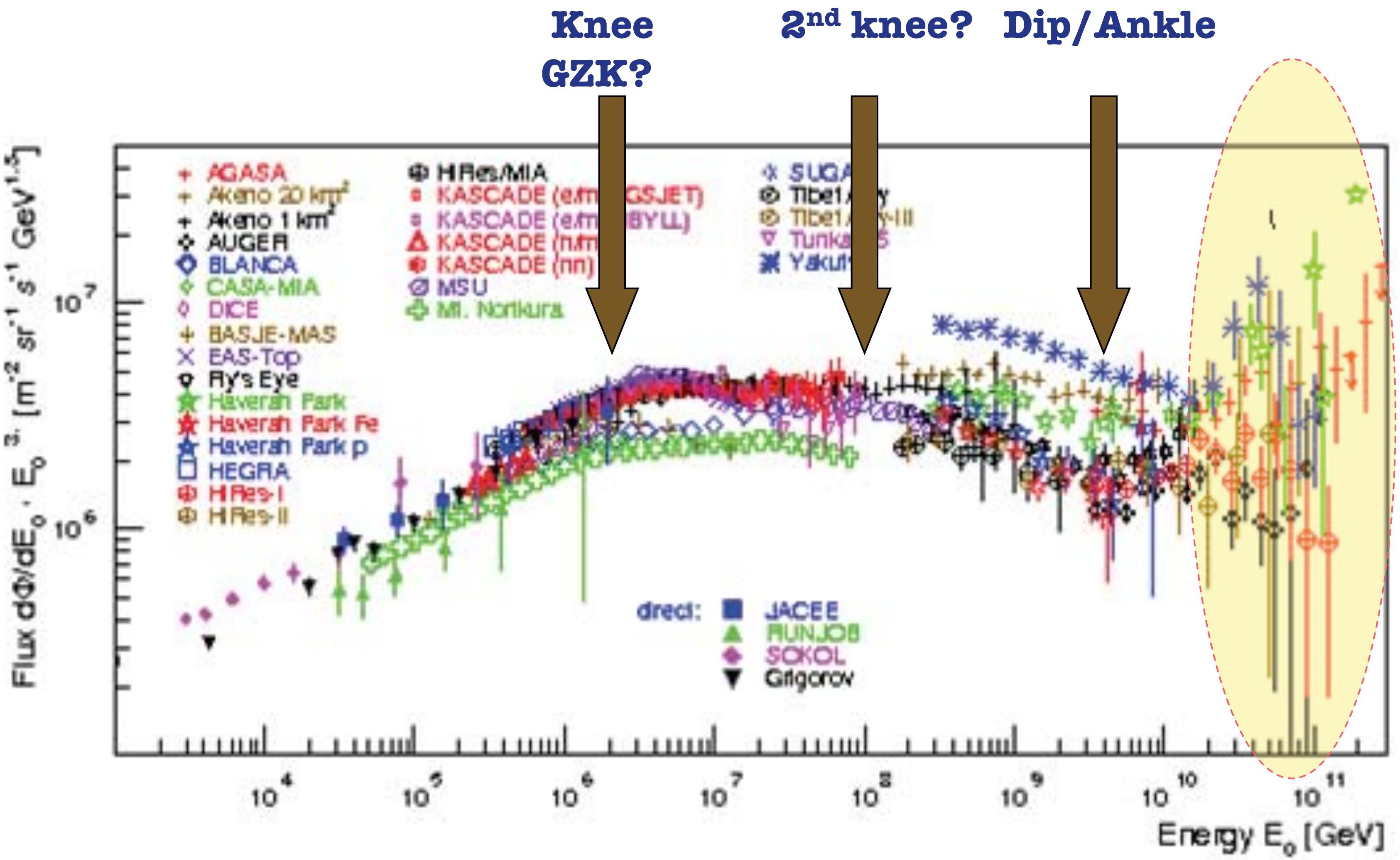
INAF/Osservatorio Astrofisico di Arcetri
Firenze
Italy

Strada Costiera 11, 34014 Trieste, Italy - Tel. +39 040 2240 111; Fax +39 040 224 163 - sci_info@ictp.it, www.ictp.it

A PROGRESS REPORT ON THE ORIGIN OF VHE COSMIC RAYS

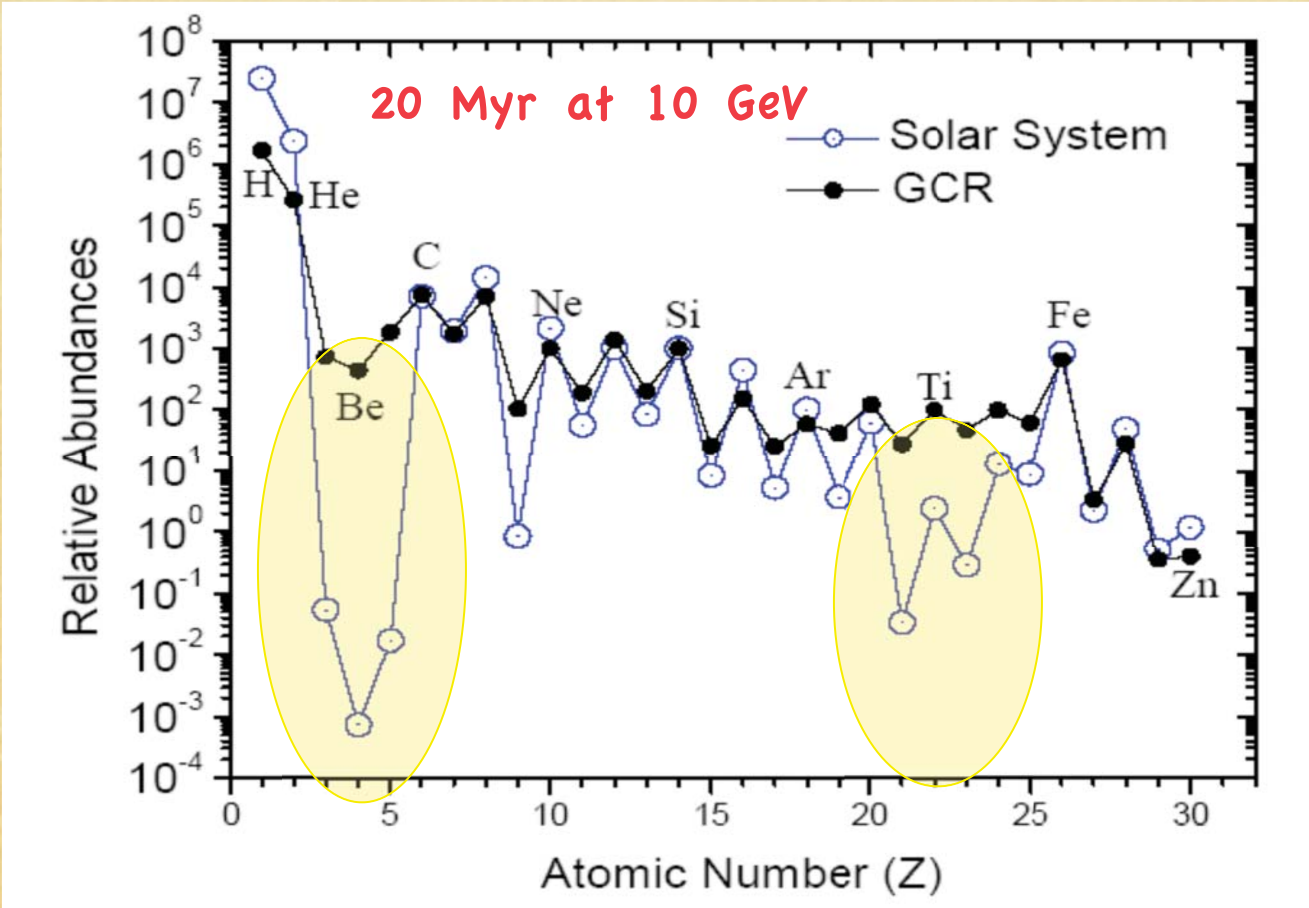
Pasquale Blasi
INAF/Osservatorio Astrofisico di Arcetri, Firenze

THE ALL-PARTICLE SPECTRUM

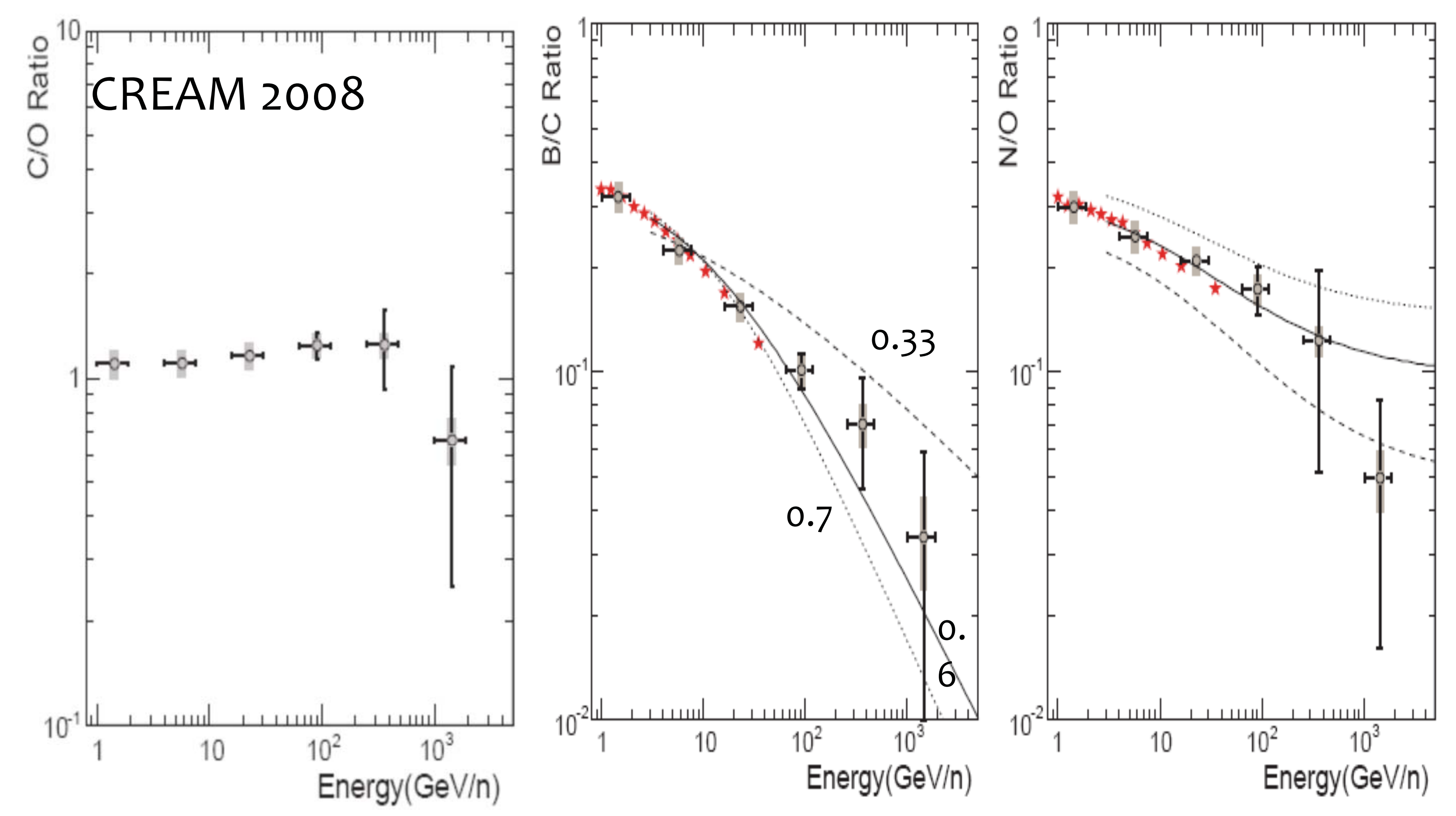


PROPAGATION IN THE GALAXY

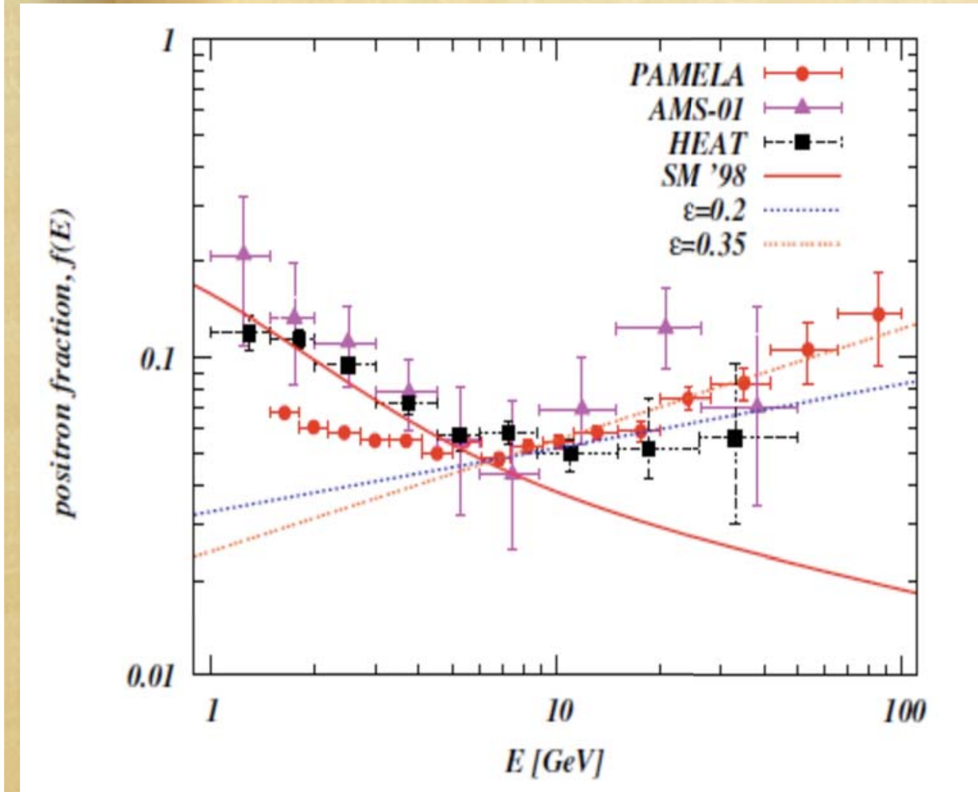
THE BULK OF COSMIC RAYS PROPAGATE DIFFUSIVELY IN THE GALAXY, THE BEST PROOF BEING THE ABUNDANCIES OF LIGHT ELEMENTS

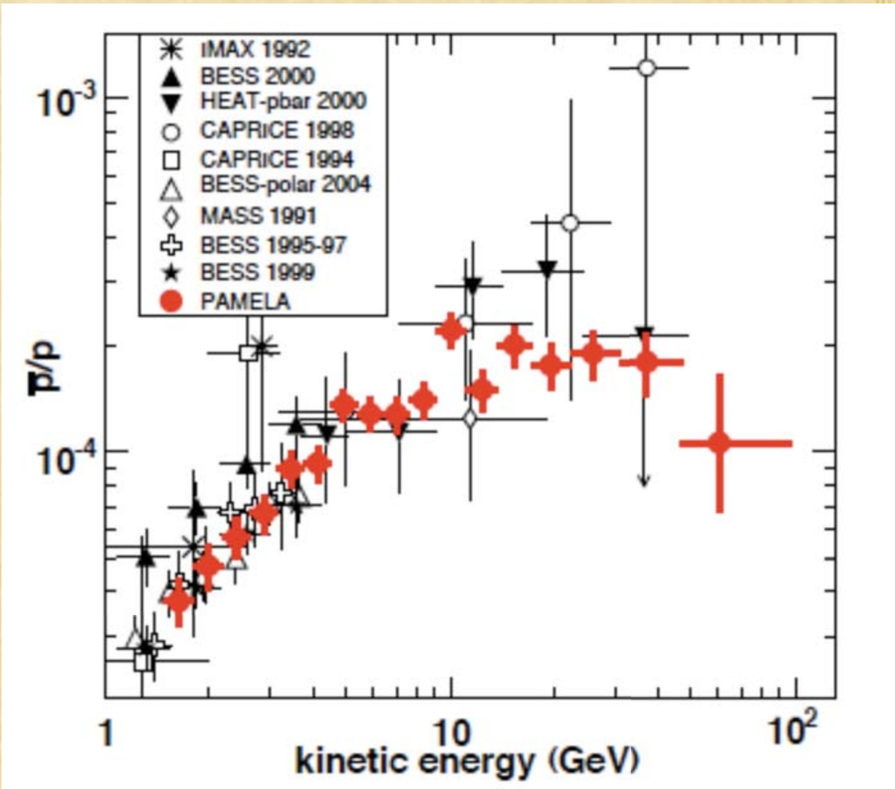


S/P RATIO AND CR DIFFUSION



COMPLICATIONS: POSITRONS and ANTIPROTONS





WHAT IS THE PROBLEM?

PRIMARY PROTONS:

$$n_{CR}(E) = \mathrm{N}_{\mathrm{CR}}(\mathrm{E})\ \mathrm{R}\ \tau_{\mathrm{esc}}(\mathrm{E}) \propto \mathrm{E}^{-\gamma}\mathrm{E}^{-\delta}$$

PRIMARY ELECTRONS: (b= d for diffusion, b=1 [or 1-(1/2)(d-1)] for losses)

$$n_e(E) = \mathrm{N}_{\mathrm{e}}(\mathrm{E})\ \mathrm{R}\ \mathrm{Min}\left[\tau_{\mathrm{esc}}(E), \tau_{loss}(E)\right] \propto E^{-\gamma_e} E^{-\beta}$$

SECONDARY POSITRONS INJECTION:

$$\mathrm{q}_{+}(\mathrm{E}')\mathrm{dE}' = \mathrm{n}_{\mathrm{CR}}(\mathrm{E})\mathrm{dE}\ \mathrm{n}_{\mathrm{H}}\ \sigma_{\mathrm{pp}}\ \mathrm{c} \propto \mathrm{E}^{-\gamma-\delta}$$

SECONDARY POSITRONS EQUILIBRIUM:

$$n_{+}(E) = q_{+}(E)\ \mathrm{Min}\left[\tau_{\mathrm{esc}}(E), \tau_{loss}(E)\right] \propto E^{-\gamma-\delta-\beta}$$

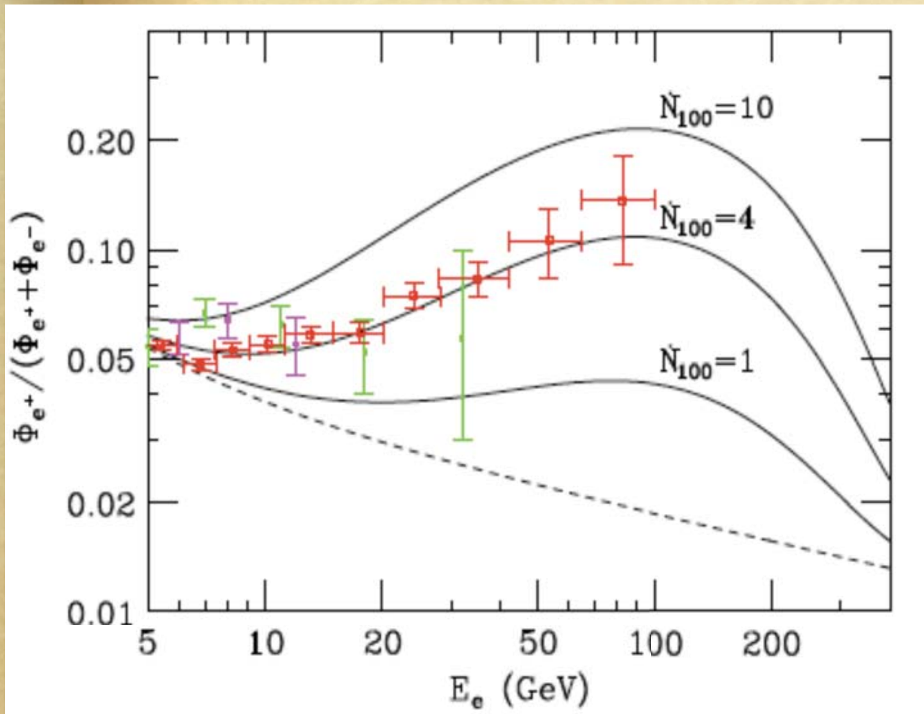
$$\frac{n_{+}}{n_e} \propto E^{-(\gamma-\gamma_e)-\delta}$$

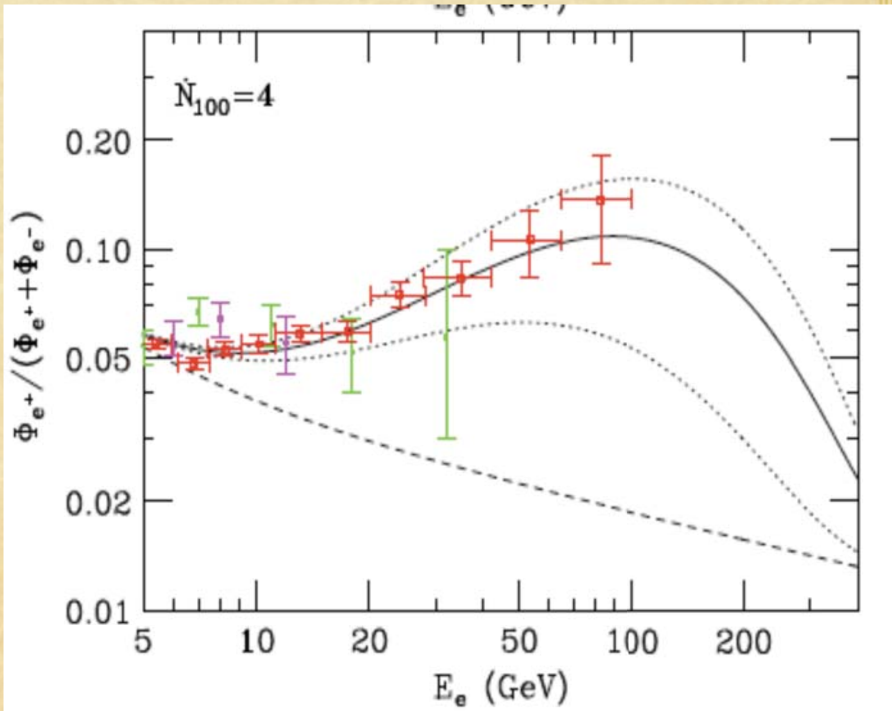
CANNOT GROW!

POSSIBLE EXPANATIONS

1. SOMETHING WRONG WITH PROPAGATION
2. PULSARS AS SOURCES OF PAIRS
3. RE-ENERGIZED PAIRS IN SNR
4. DARK MATTER? (IT CAN'T BE THE USUAL THERMAL SUSY WIMPS)

PULSARS

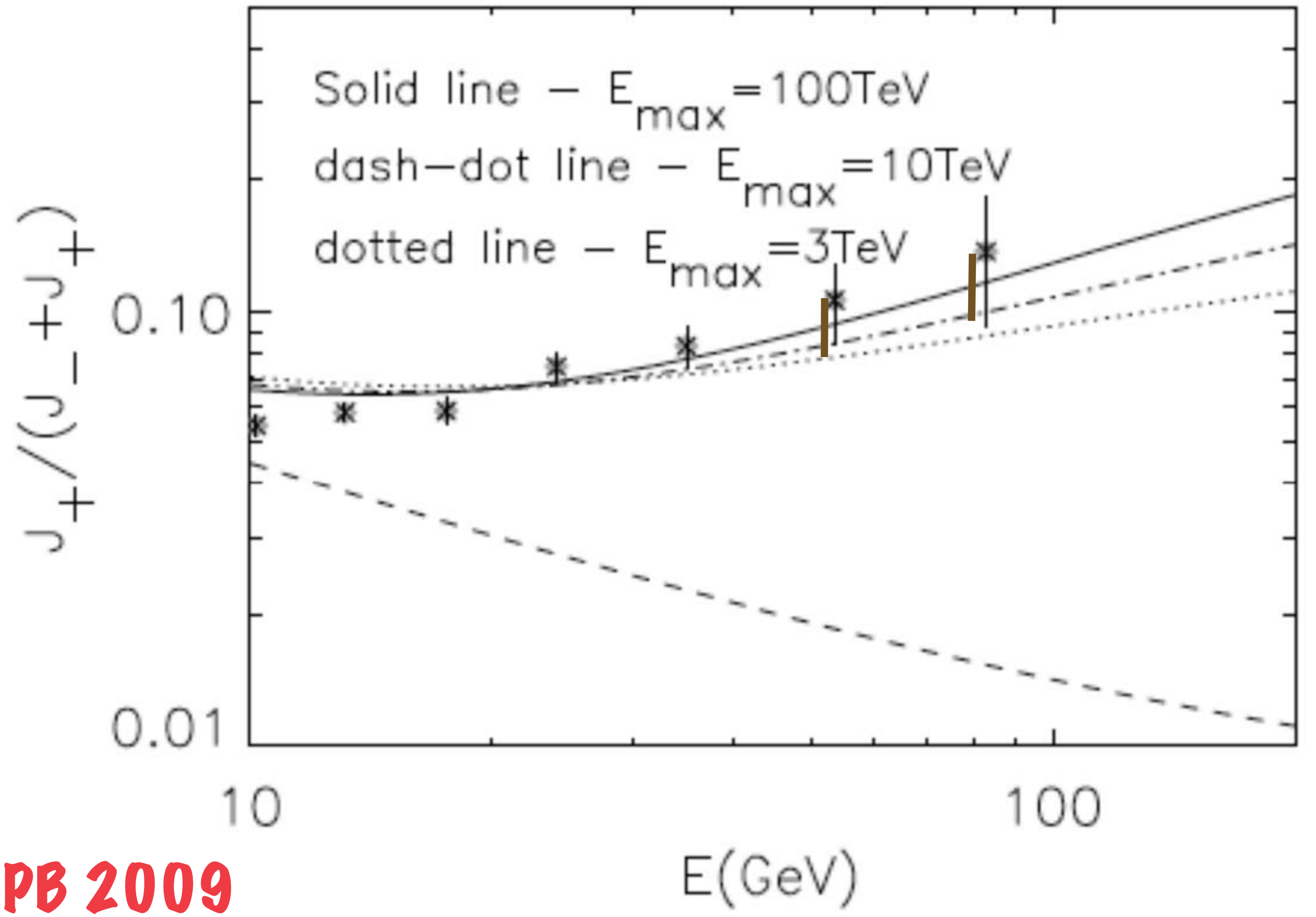




Hooper, PB, Serpico
2009

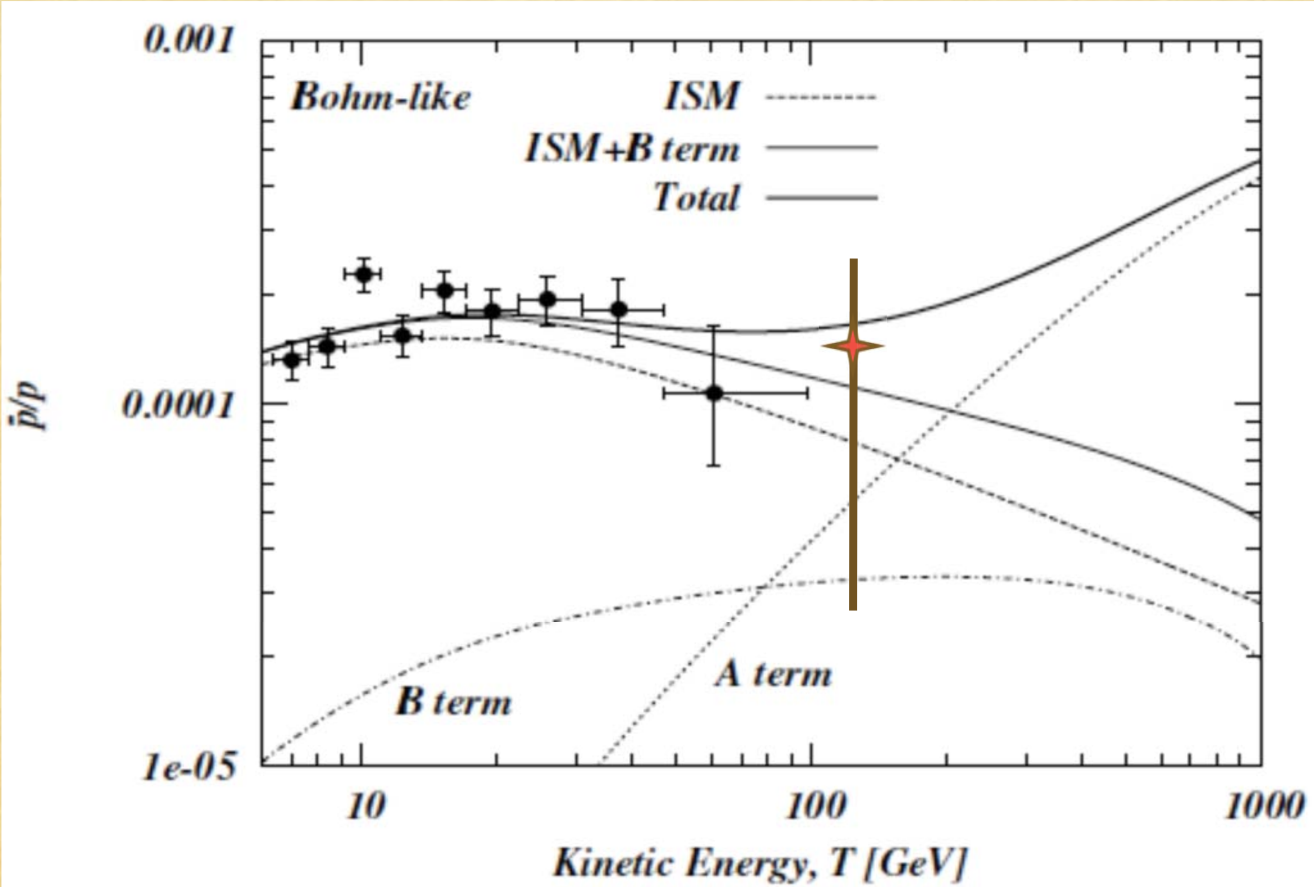
NO ANTIPROTONS
PRODUCED !

RE-ENERGIZED PAIRS IN SNR

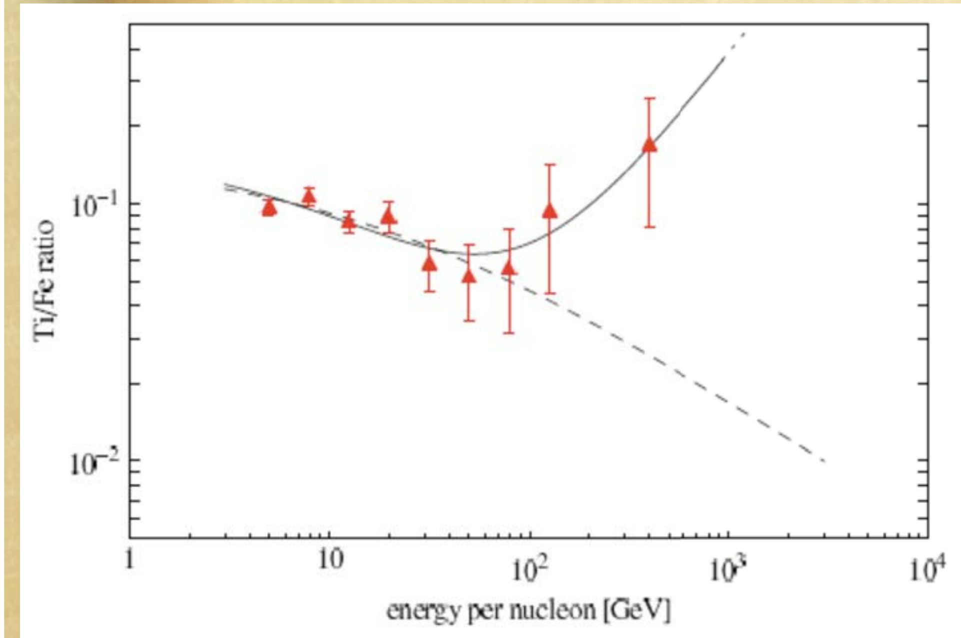


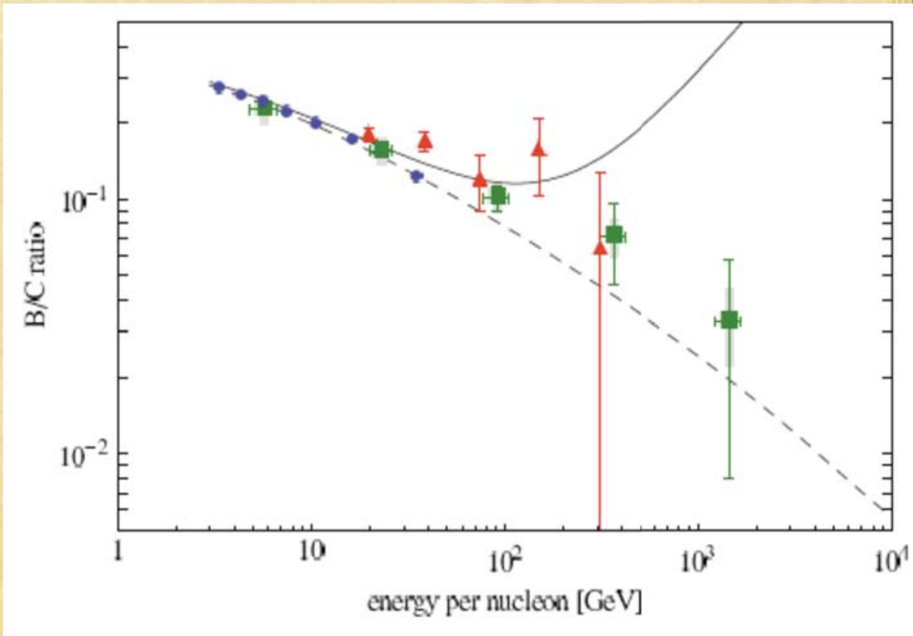
PB 2009

COLLATERAL EFFECTS:
1. ANTIPROTONS



COLLATERAL EFFECTS:
2. SECONDARY NUCLEI

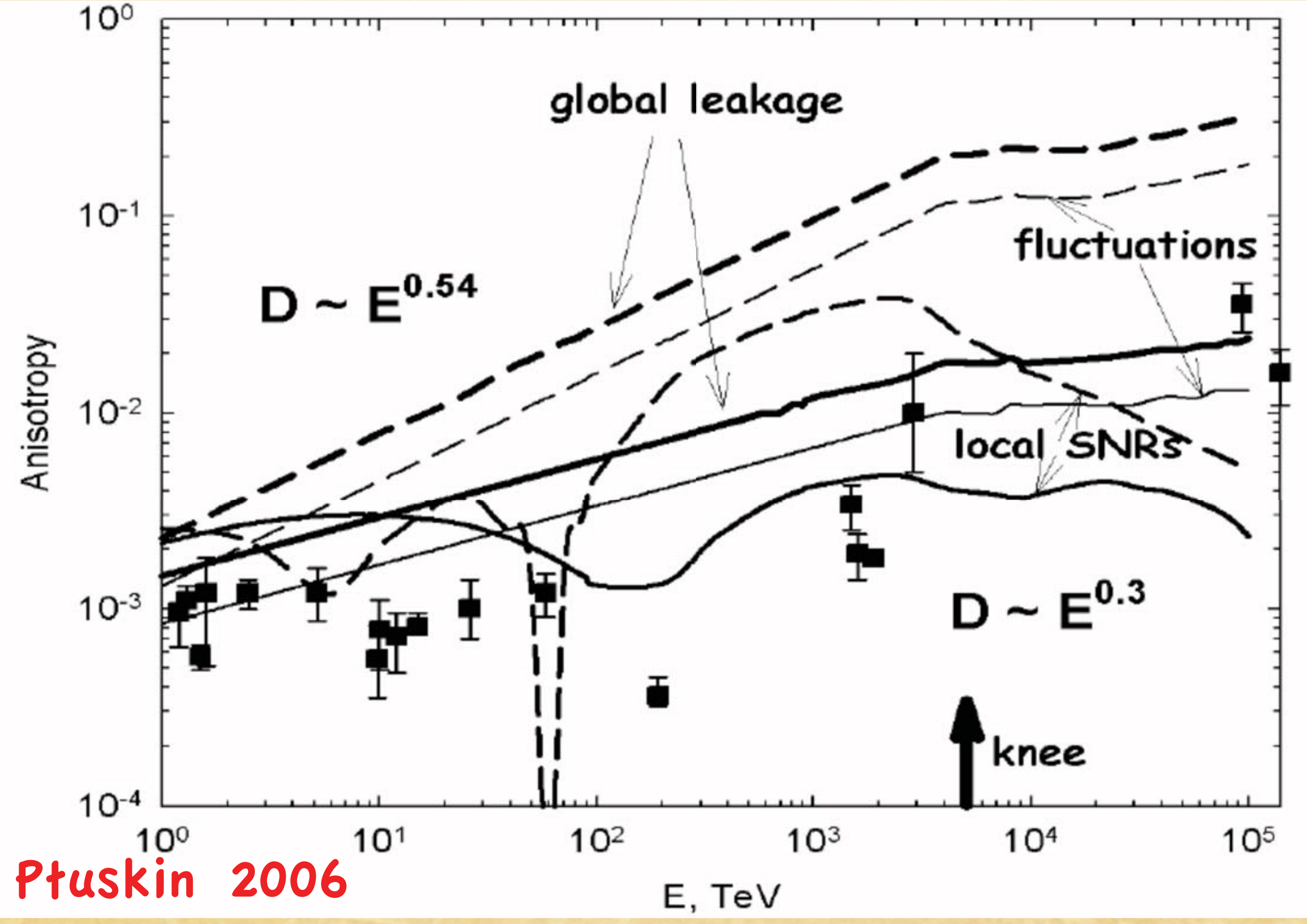




Ti/Fe **B/C**

Mertsch & Sarkar 2009

SOME MORE COMPLICATIONS: ANISOTROPY



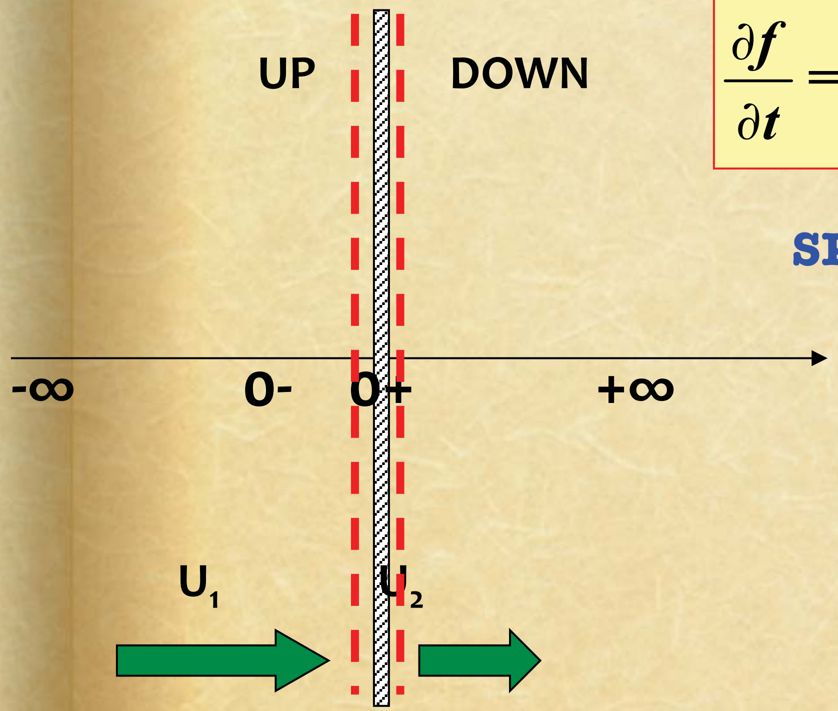
Ptuskin 2006

PARTICLE ACCELERATION

THE SUPERNOVA PARADIGM

TEST PARTICLE THEORY OF SNR→CR

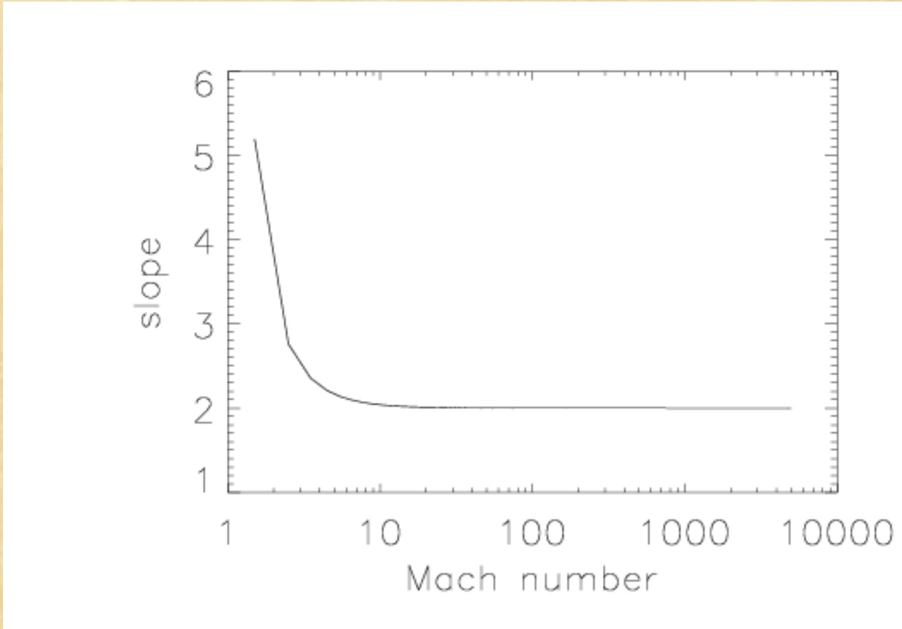
$$\frac{\partial f}{\partial t} = \frac{\partial}{\partial x}\left[D\frac{\partial f}{\partial x}\right] - u\frac{\partial f}{\partial x} + \frac{1}{3}\frac{du}{dx}p\frac{\partial f}{\partial p} + Q(x,p,t)$$



SPECTRUM

$$N(E) \propto \left(\frac{\mathrm{E}}{\mathrm{E}_0}\right)^{-\gamma} \qquad \gamma = \frac{R+2}{R-1}$$

R COMPRESSION FACTOR



1. Power law spectrum
2. Slope only F(R)
3. No dependence on diffusion
4. For strong shocks slope ~2
5. No absolute normalization

Maximum energy

ACCELERATION TIME

$$\tau_{acc} = \frac{3}{U_1 - U_2}\left[\frac{D_1(E)}{U_1} + \frac{D_2(E)}{U_2}\right]$$

What if we use the ISM diffusion coefficient inferred from B/C?

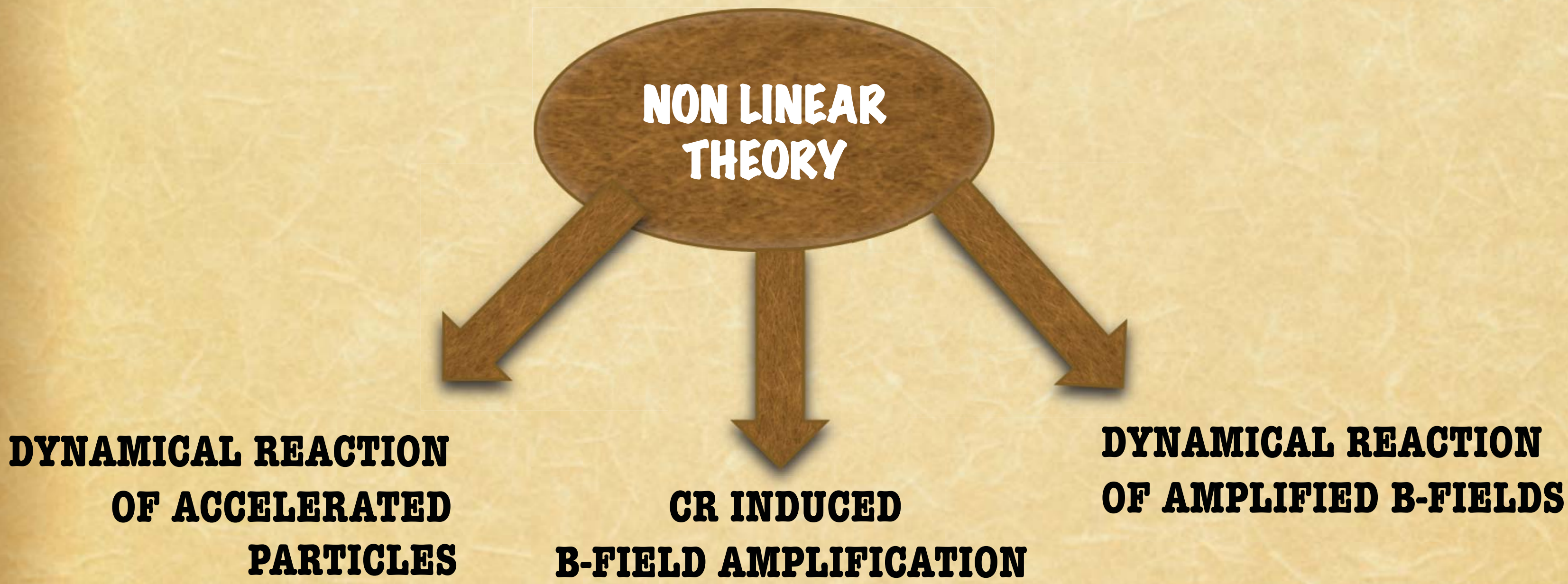
$$\tau_{acc} \approx \tau_{age}$$ → E_{max} ~ **1-100 GeV**

IF DIFFUSIVE SHOCK ACCELERATION IS THE CONVERSION MECHANISM IN SNR, IT MUST BE COMPLETED WITH SOME PROCESS THAT ALLOWS TO REACH PeV ENERGIES

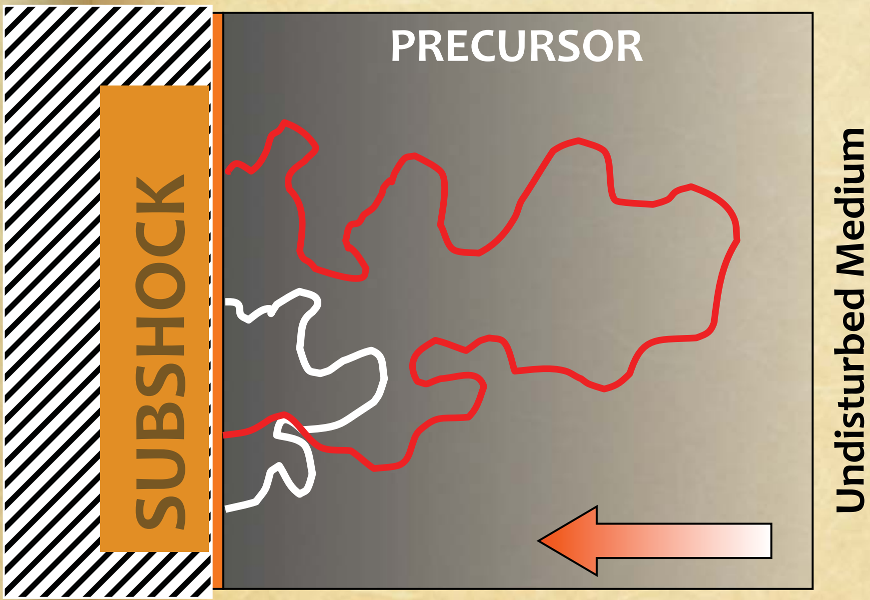
BEYOND TEST PARTICLES: *Non linear DSA*

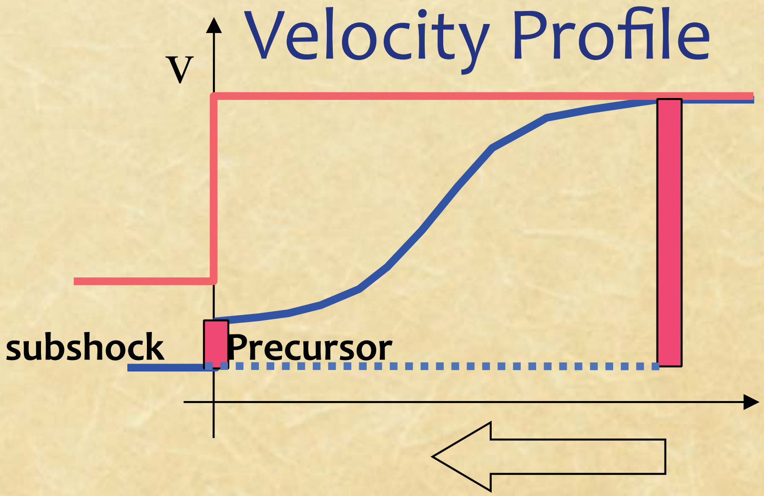
Berezhko & Voelk, PB, Amato & PB, Ellison et al…

1. TEST PARTICLE THEORY PROVIDES NO INFO ON ACCELERATION EFFICIENCY
2. THE REQUIRED EFFICIENCIES ARE SUCH THAT CR SHOULD EXERT A DYNAMICAL REACTION ON THE SYSTEM
3. IN TP THEORY THERE IS NO EASY WAY TO REACH THE KNEE



DYNAMICAL REACTION



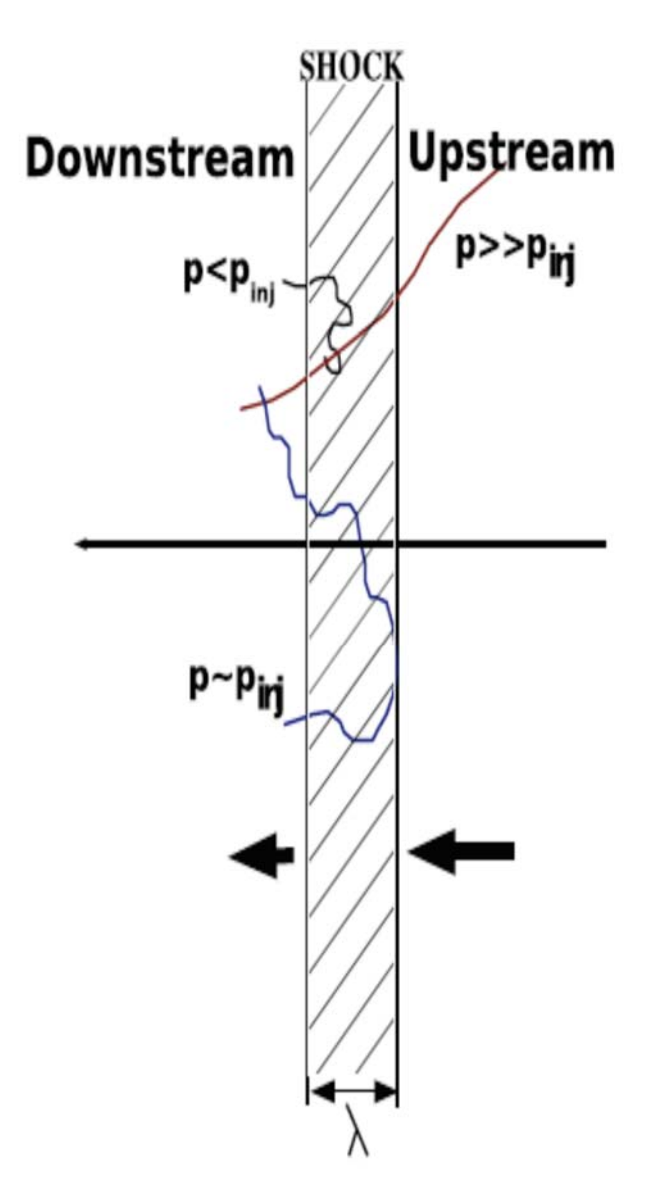


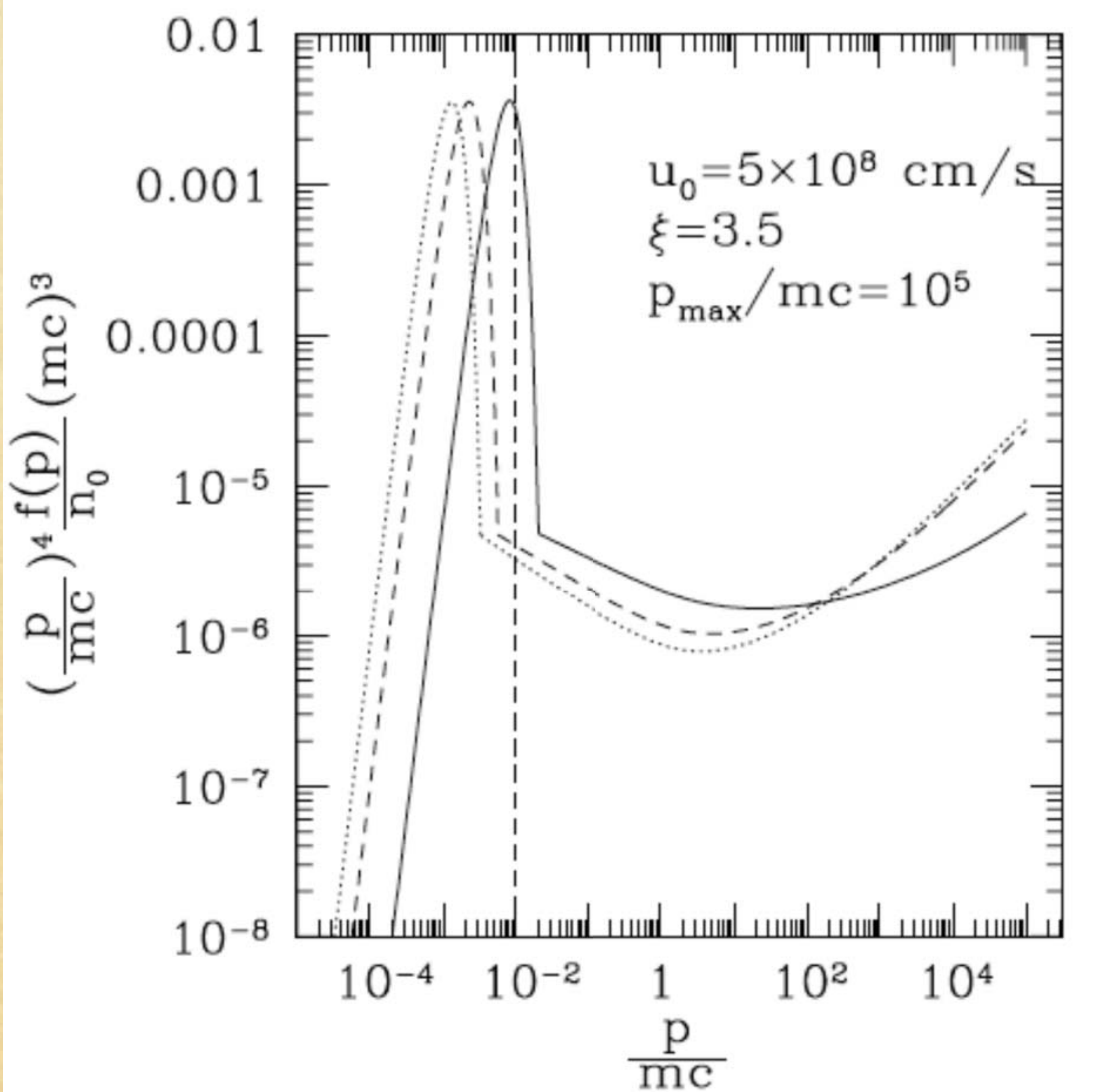
CR TRANSPORT EQUATION

+

MASS, MOMENTUM, ENERGY CONSERVATION EQUATIONS

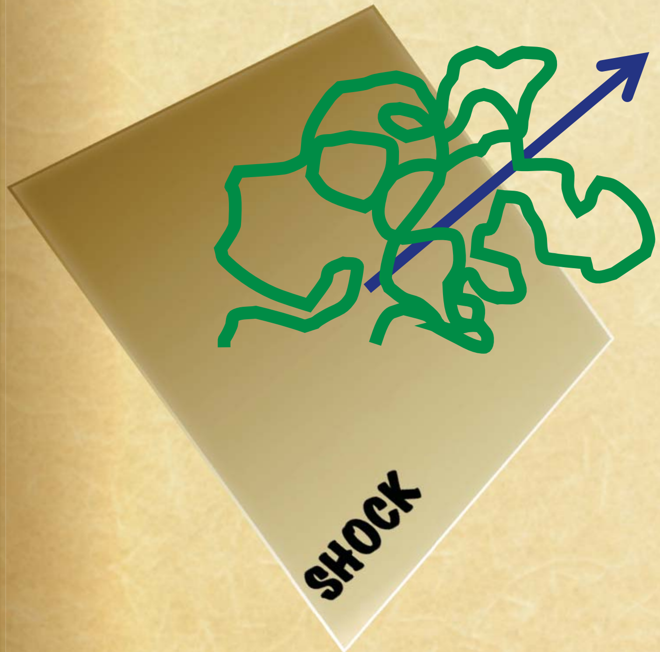
1. NO POWER LAW SPECTRA
2. HIGH ACCEL. EFFICIENCY
3. REDUCED HEATING
4. ESCAPE FLUX





PB, Gabici & Vannoni 2005

MAGNETIC FIELD AMPLIFICATION



SMALL PERTURBATIONS IN THE LOCAL B-FIELD CAN BE AMPLIFIED BY THE SUPER-ALFVENIC STREAMING OF THE ACCELERATED PARTICLES

$$\tau = \frac{1}{\Omega(\delta B / B)^2}$$

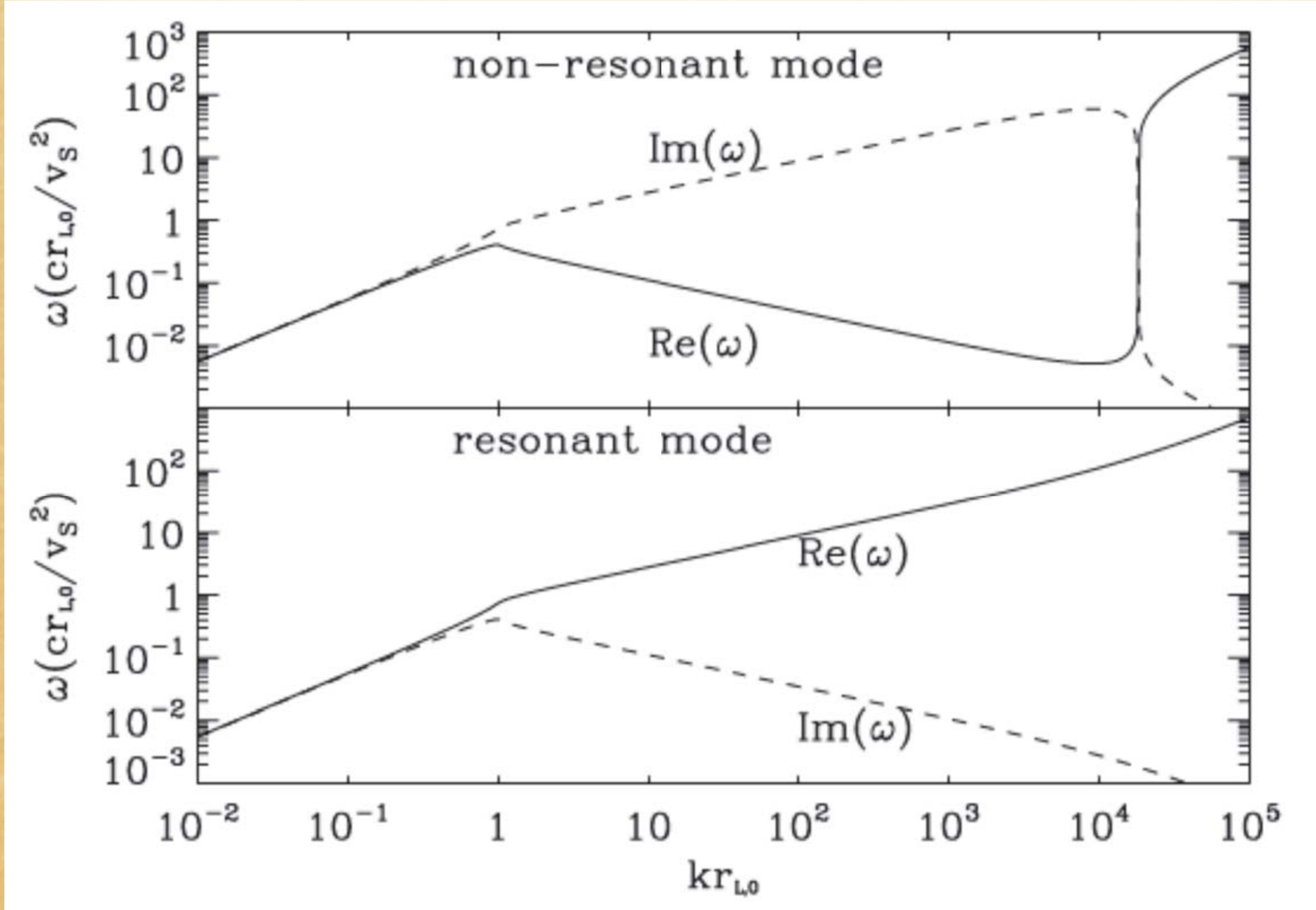
$$\frac{dP_{CR}}{dt} = \frac{n_{CR} m_p \gamma_{CR} (v_S - v_A)}{\tau}$$

$$\frac{dP_W}{dt} = \Gamma_W \frac{\delta B^2}{4\pi v_A}$$

$$\Gamma_W = \frac{n_{CR}}{n} \left(\frac{v_S - v_A}{v_A} \right) \Omega_{cyc}$$

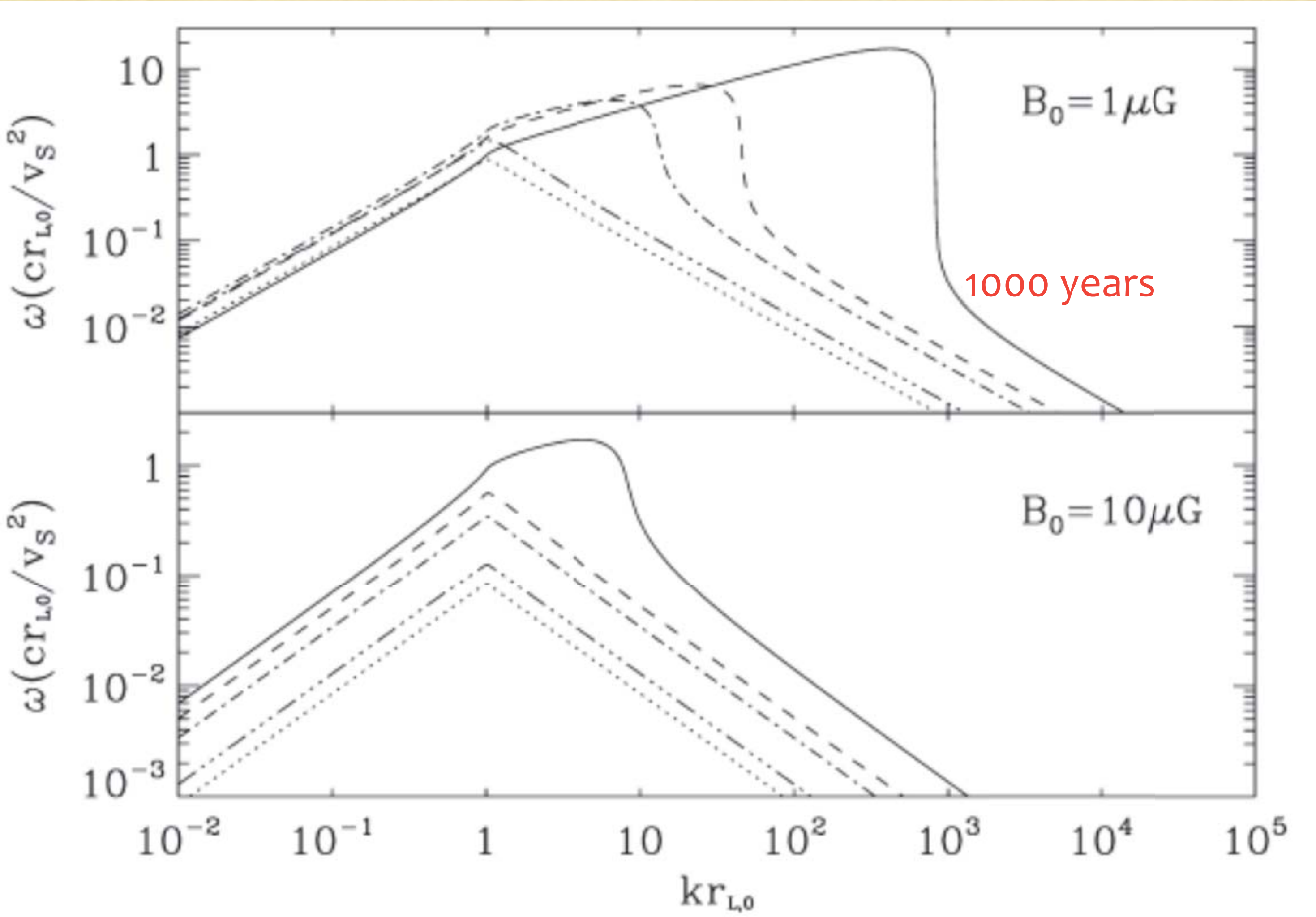
GROWTH RATE

GROWING MODES



Amato & PB 2009

RESONANT vs NON-RESONANT MODES



Amato & PB 2009

SATURATION

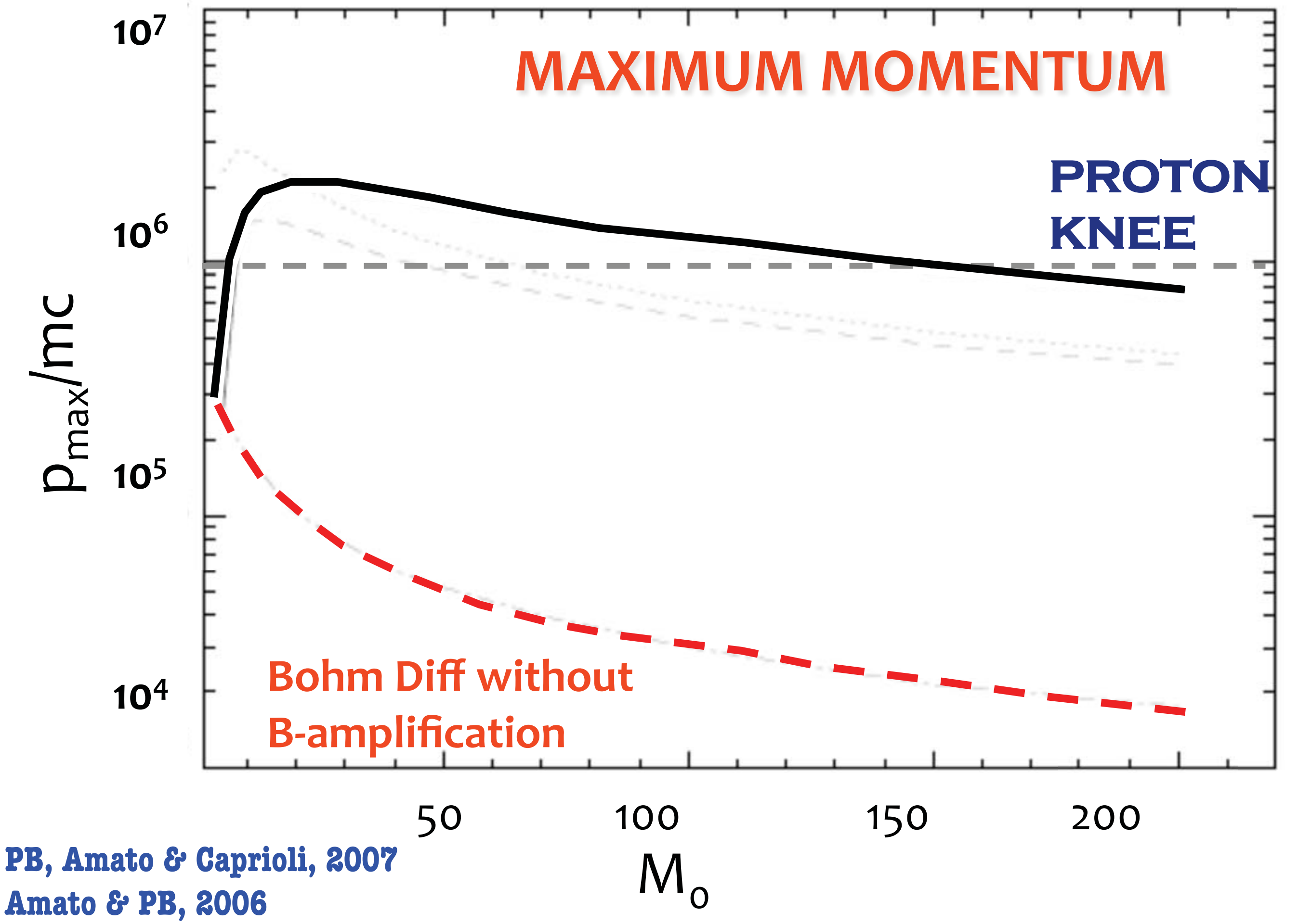
ALL PREVIOUS RESULTS ARE OBTAINED IN PERTURBATIVE THEORY BUT THEY LEAD TO NON-PERTURBATIVE CONCLUSIONS (dB/B>>1).

HARD TO PREDICT THE REAL SATURATION LEVEL (EVEN PIC SIMULATIONS DISAGREE ON CONCLUSIONS...

BUT IT IS SUGGESTIVE THAT THE VALUES INFERRED FROM PERTURBATIVE THEORY HINT TO

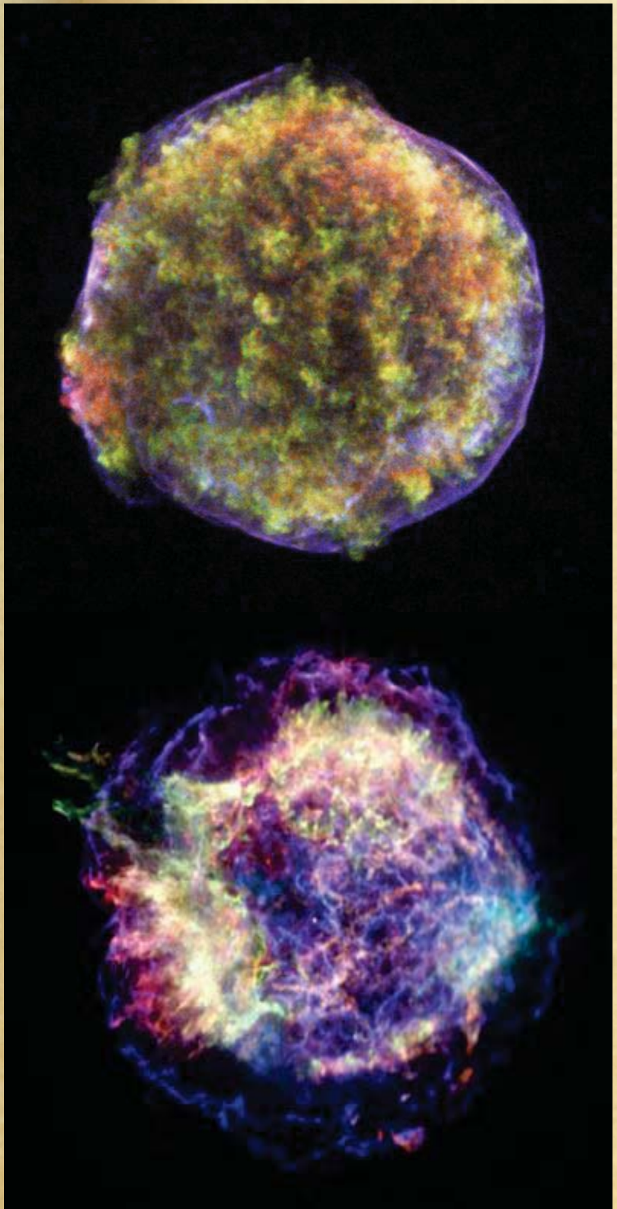
$$\delta B \approx 100\ \mu G$$

WHY IS IT INTERESTING: I. Reaching the knee?



PB, Amato & Caprioli, 2007
Amato & PB, 2006

WHY IS IT INTERESTING:
II. Large B observed?



TYPICAL THICKNESS OF FILAMENTS:
10^{-2} -10^{-3} pc

The synchrotron limited thickness is:

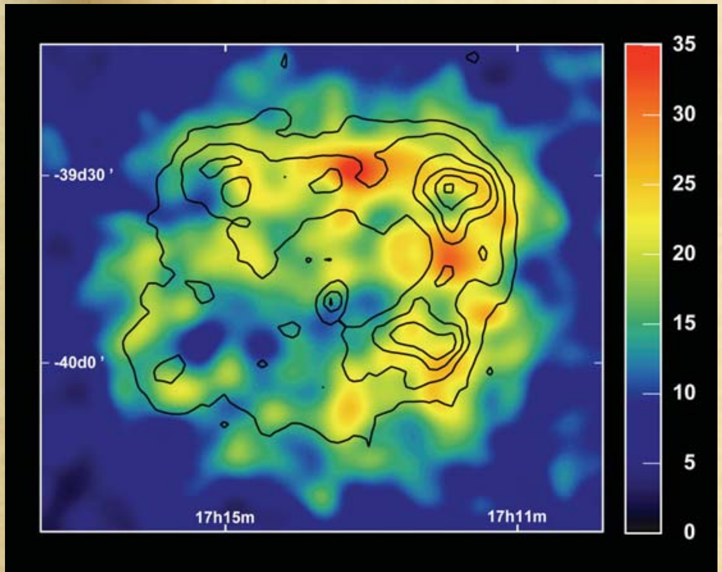
$$\Delta x = \sqrt{4D(E)\tau_{syn}(E)} \approx 4\,pc\; B_{\mu}^{-3/2}$$

$$B \approx 100\ \mu\text{Gauss}$$

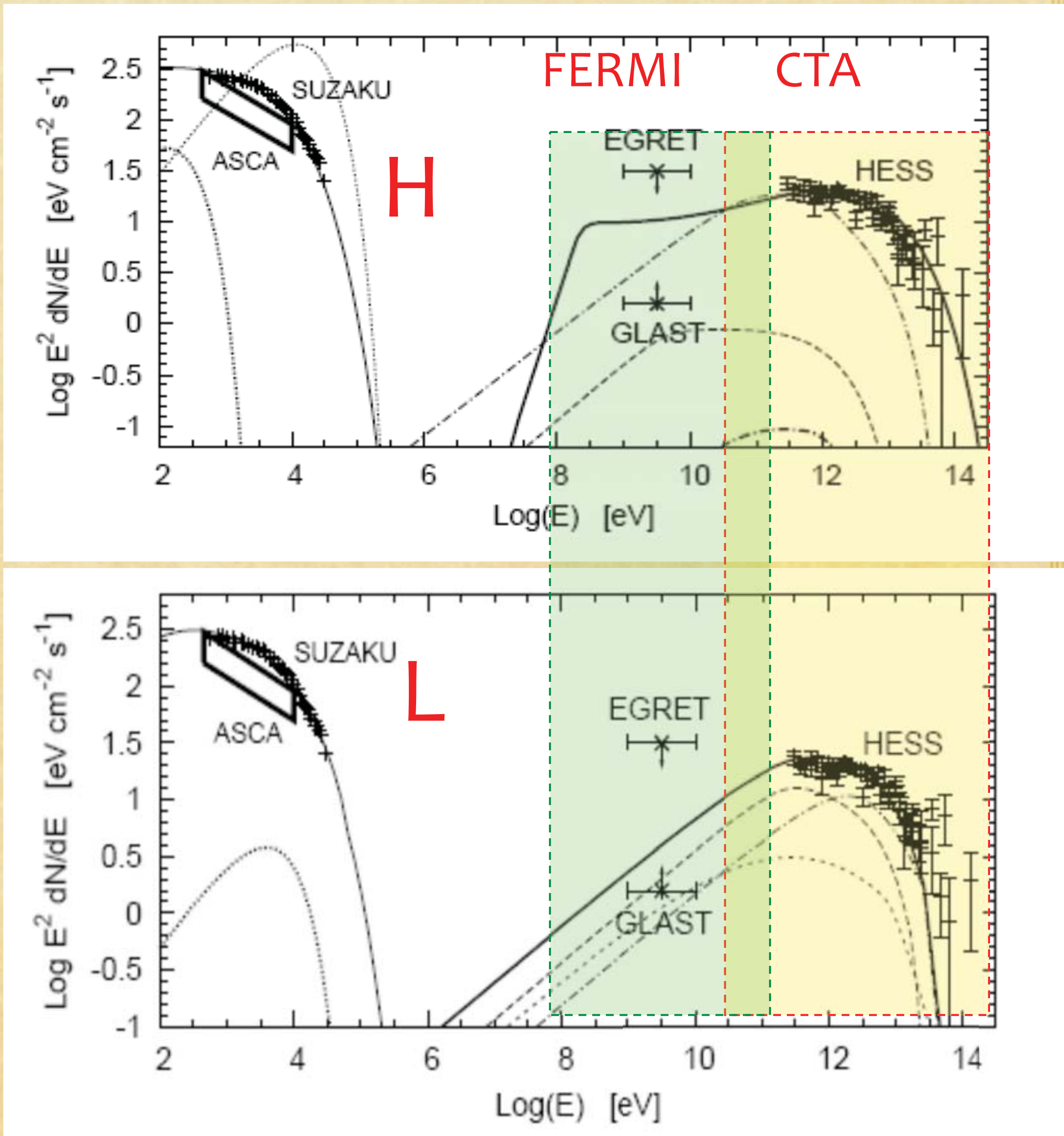
DYNAMICAL ROLE OF B

1. LARGE B INCREASE THE MAX MOMENTUM
2. HIGH MAX MOMENTUM MODIFY THE SHOCK
3. SHOCK MODIFICATION → CONCAVE SPECTRA
4. LARGE B → REDUCE MODIFICATION → LESS CONCAVE SPECTRA (Rtot~10) [Caprioli et al. 2008]

PHENOMENOLOGY OF INDIVIDUAL SNR



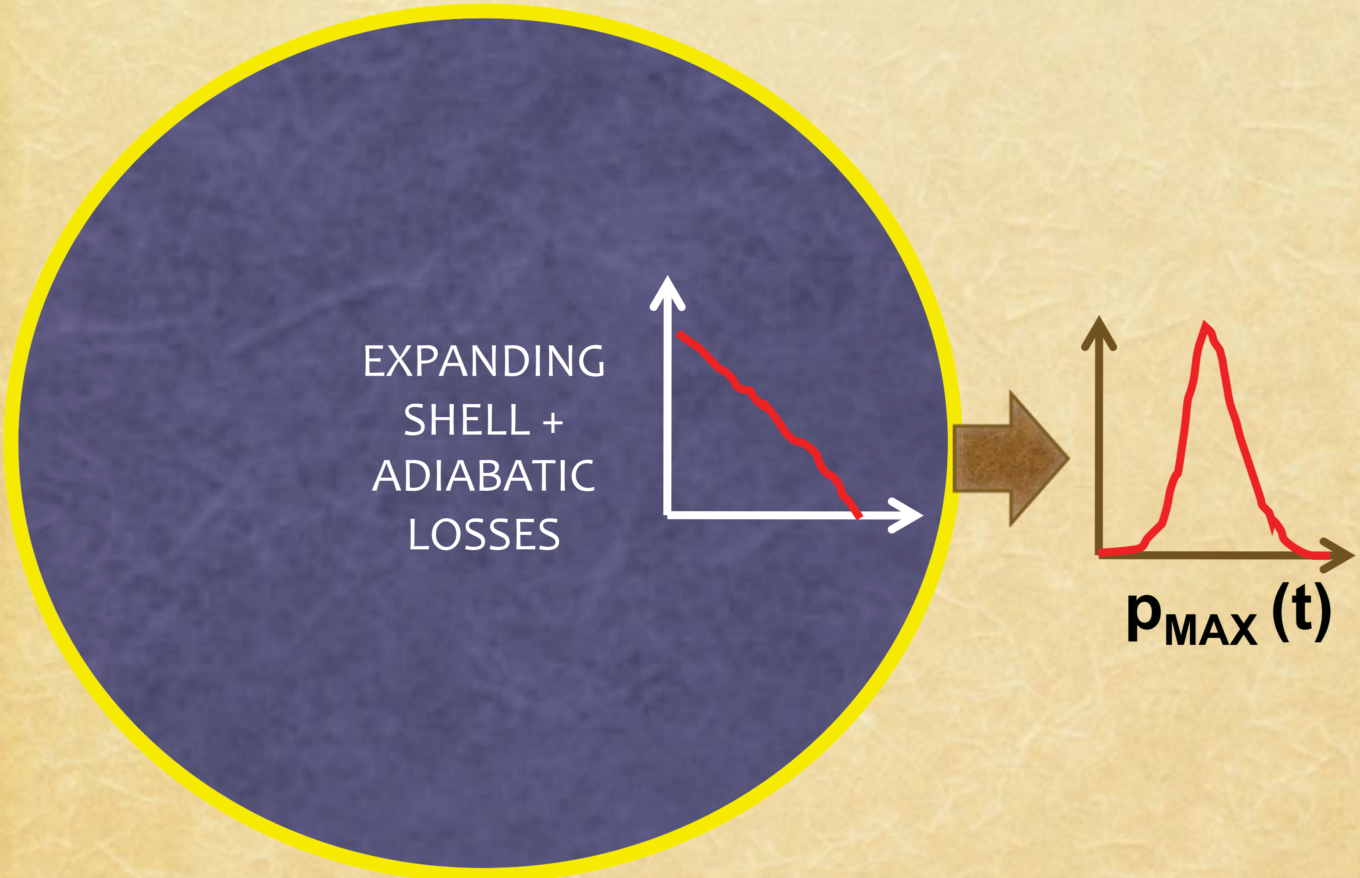
Aharonian et al. 2007



Morlino, Amato & PB 2009

CRs versus ACCELERATED PARTICLES

WHAT IS THE SPECTRUM OF CR AT EARTH?



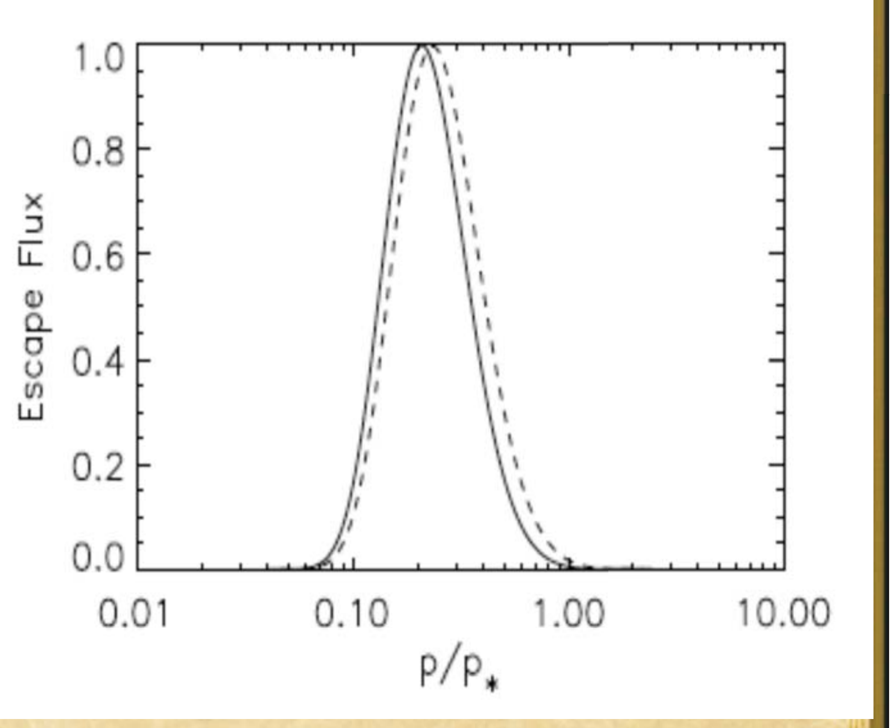
ESCAPE FLUX WITH TIME

Caprioli, PB & Amato 2009

$$E_{MAX}(t) \propto \xi_c(t)\, t^{-1/2}$$

$$R_{sh}(t) = 2.7 \times 10^{19}\mathrm{cm}\left(\frac{E_{51}}{n_1}\right)^{1/5} t_{kyr}^{2/5}$$

$$V_{sh}(t) = 4.7 \times 10^{8}\mathrm{cm/s}\left(\frac{E_{51}}{n_1}\right)^{1/5} t_{kyr}^{-3/5}$$

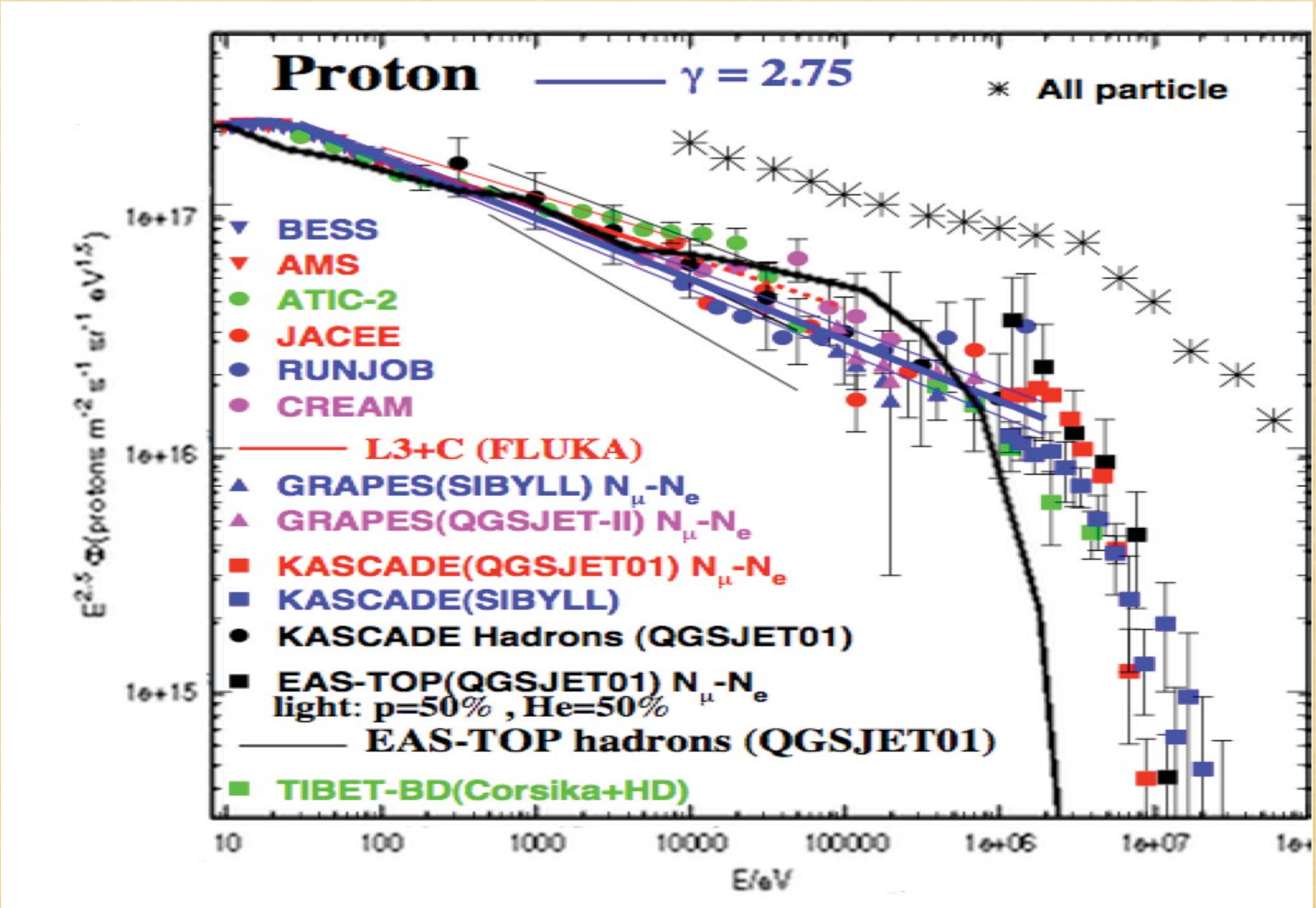


$$Q(E)dE \approx F_{esc}(t)\ \frac{1}{2}\rho V_s^3\ 4\pi R_{sh}^2\ \frac{dE_{max}}{dt}\frac{dE}{E} \propto\ t^{1/2}\frac{dE}{E} \propto\ E^{-2}\,dE$$

E^{-2} WITH NO CONNECTION WITH THE INTRINSIC SPECTRUM

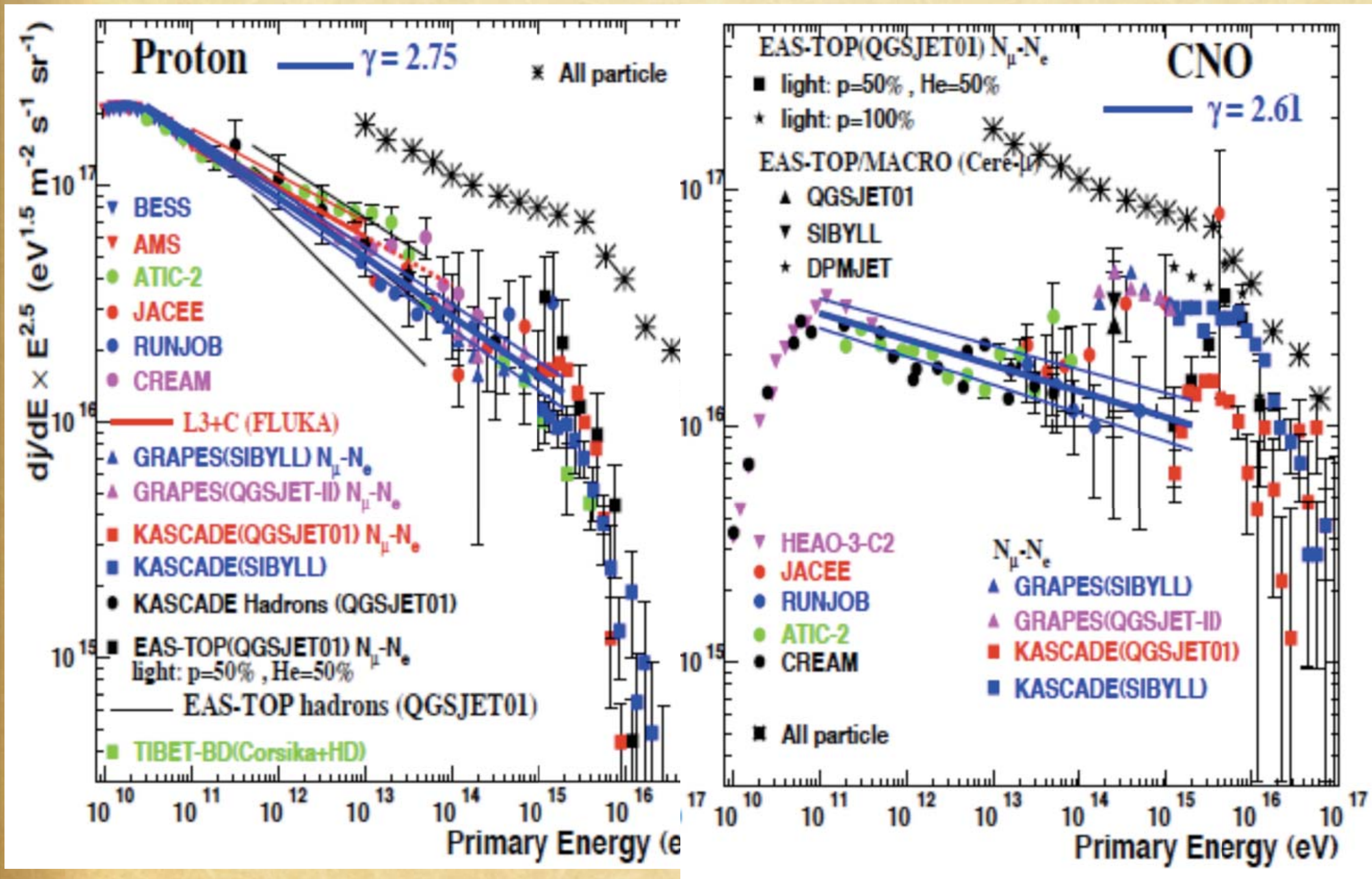
PROTON SPECTRUM AT EARTH

EVIDENCE FOR A CUTOFF!



Caprioli, PB & Amato 2009 Data from Bertaina et al. 2008

SPECTRA



Proton
γ = 2.75
All particle
BESS
AMS
ATIC-2
JACEE
RUNJOB
CREAM
L3+C (FLUKA)
GRAPES(SIBYLL) Nμ-Ne
GRAPES(QGSJET-II) Nμ-Ne
KASCADE(QGSJET01) Nμ-Ne
KASCADE(SIBYLL)
KASCADE Hadrons (QGSJET01)
EAS-TOP(QGSJET01) Nμ-Ne
light: p=50% , He=50%
EAS-TOP hadrons (QGSJET01)
TIBET-BD(Corsika+HD)
dJ/dE × E^2.5 (eV^1.5 m^-2 s^-1 sr^-1)
Primary Energy (e
CNO
γ = 2.61
EAS-TOP(QGSJET01) Nμ-Ne
light: p=50% , He=50%
light: p=100%
EAS-TOP/MACRO (Cere-μ)
QGSJET01
SIBYLL
DPMJET
HEAO-3-C2
JACEE
RUNJOB
ATIC-2
CREAM
Nμ-Ne
GRAPES(SIBYLL)
GRAPES(QGSJET-II)
KASCADE(QGSJET01)
KASCADE(SIBYLL)
All particle
Primary Energy (eV)

SOME IMPLICATIONS

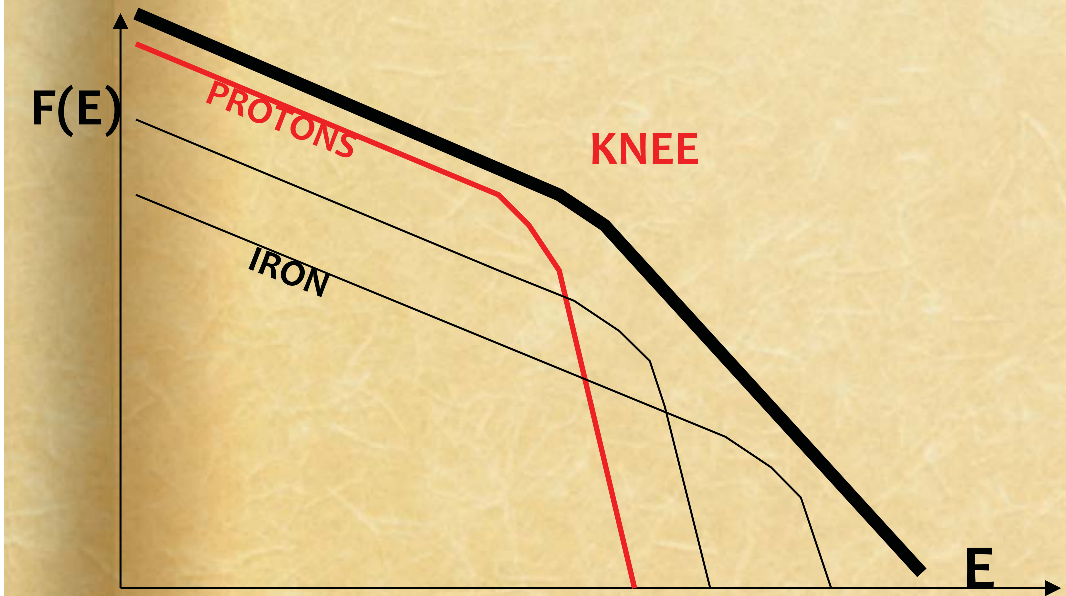
1. PROTONS ARE EXPECTED TO BE ACCELERATED TO ~10^6 GeV

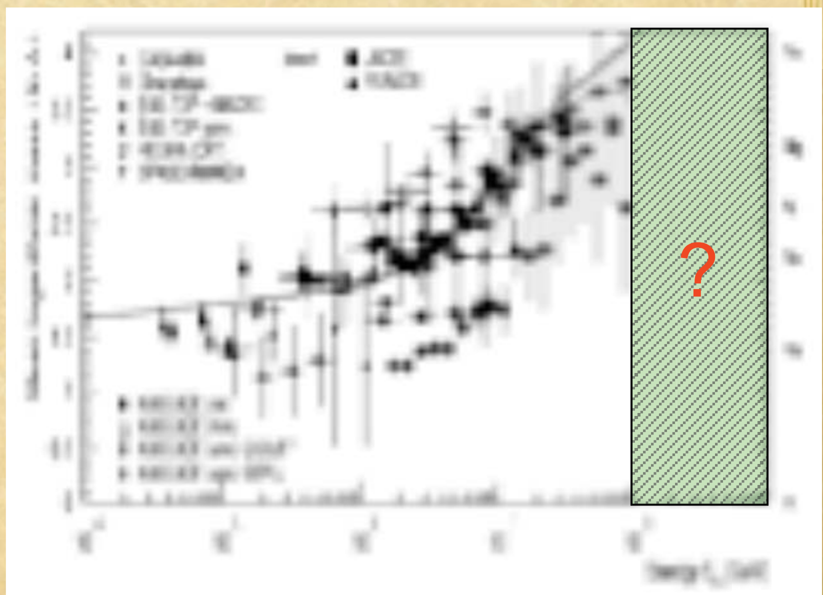
2. ACCELERATION IS Z DEPENDENT→ $E_{MAX}(Z)=Z\ E_{MAX}$

3. THE KNEE IS LIKELY TO BE THE RESULT OF OVERLAP ON THE MAX ENERGY OF EACH SPECIE

....

4. GALACTIC CRs SHOULD END WITH IRON @ ~10^{17} eV





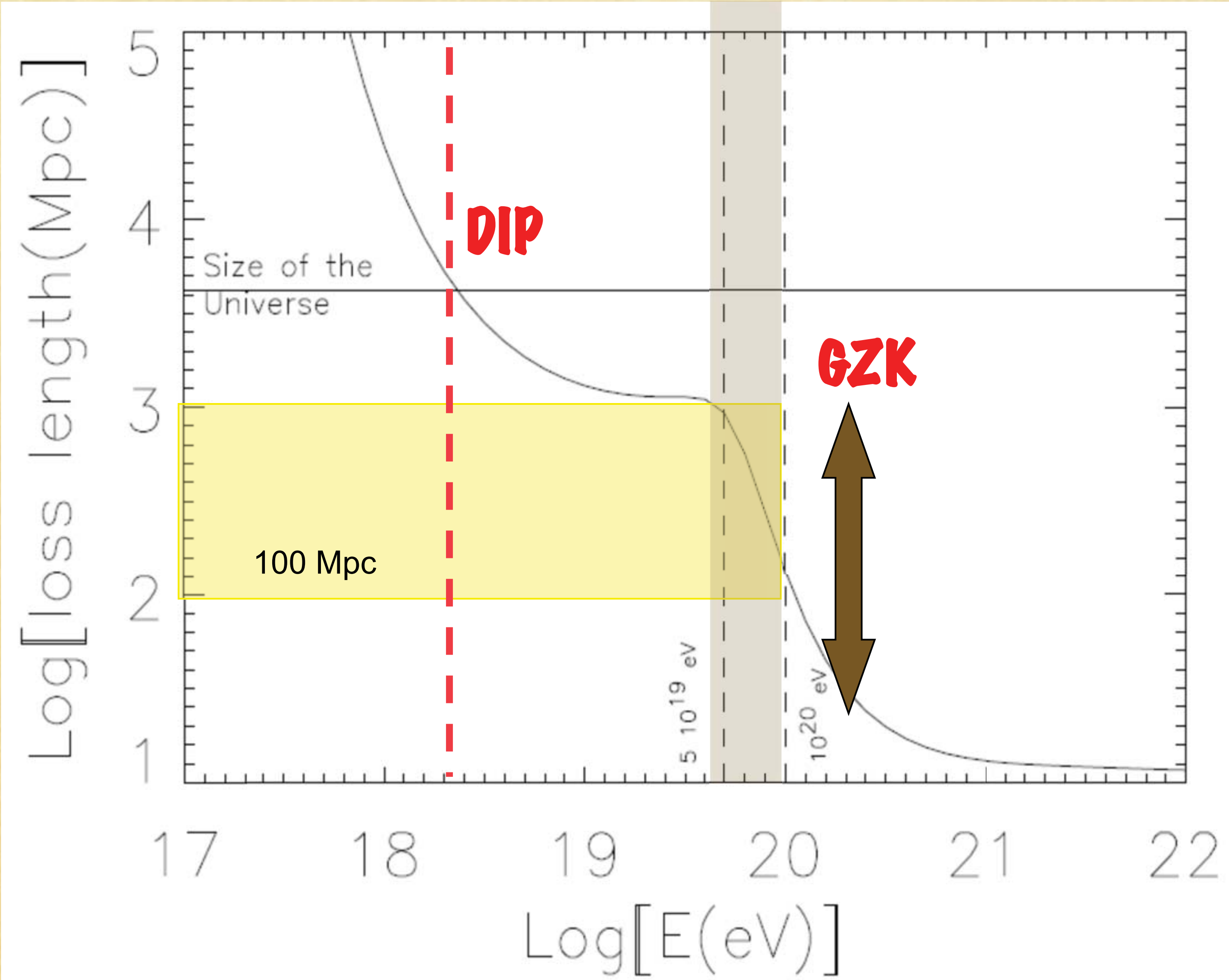
The Transition

1. The SNR paradigm hints to a galactic CR spectrum ending at ~a few 10^{17} eV

2. Observations also suggest the same trend

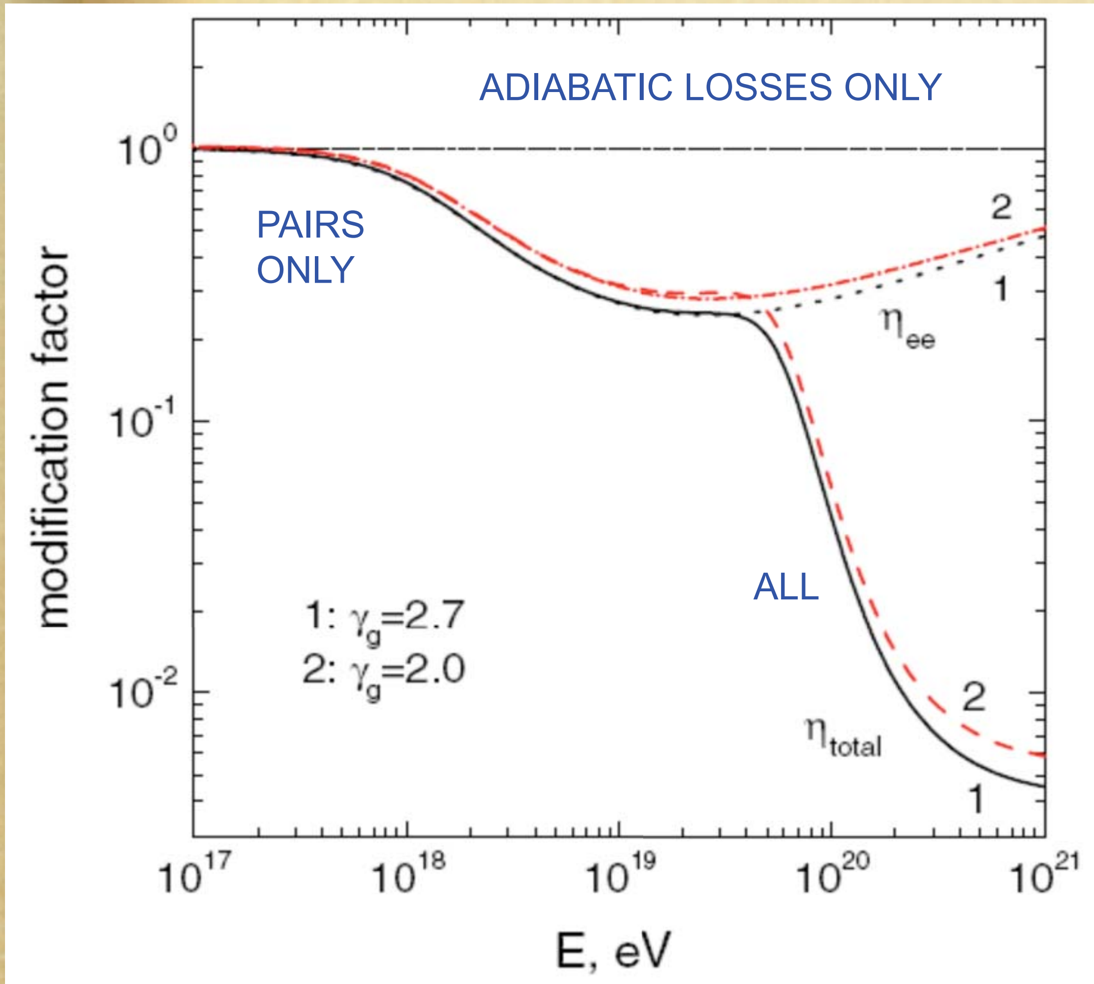
So where does the spectrum of Galactic CR end and the extragal one starts?

PROPAGATION OF PROTONS



THE MODIFICATION FACTOR

ONE MAY DEFINE THE SO CALLED MODIFICATION FACTOR AS:

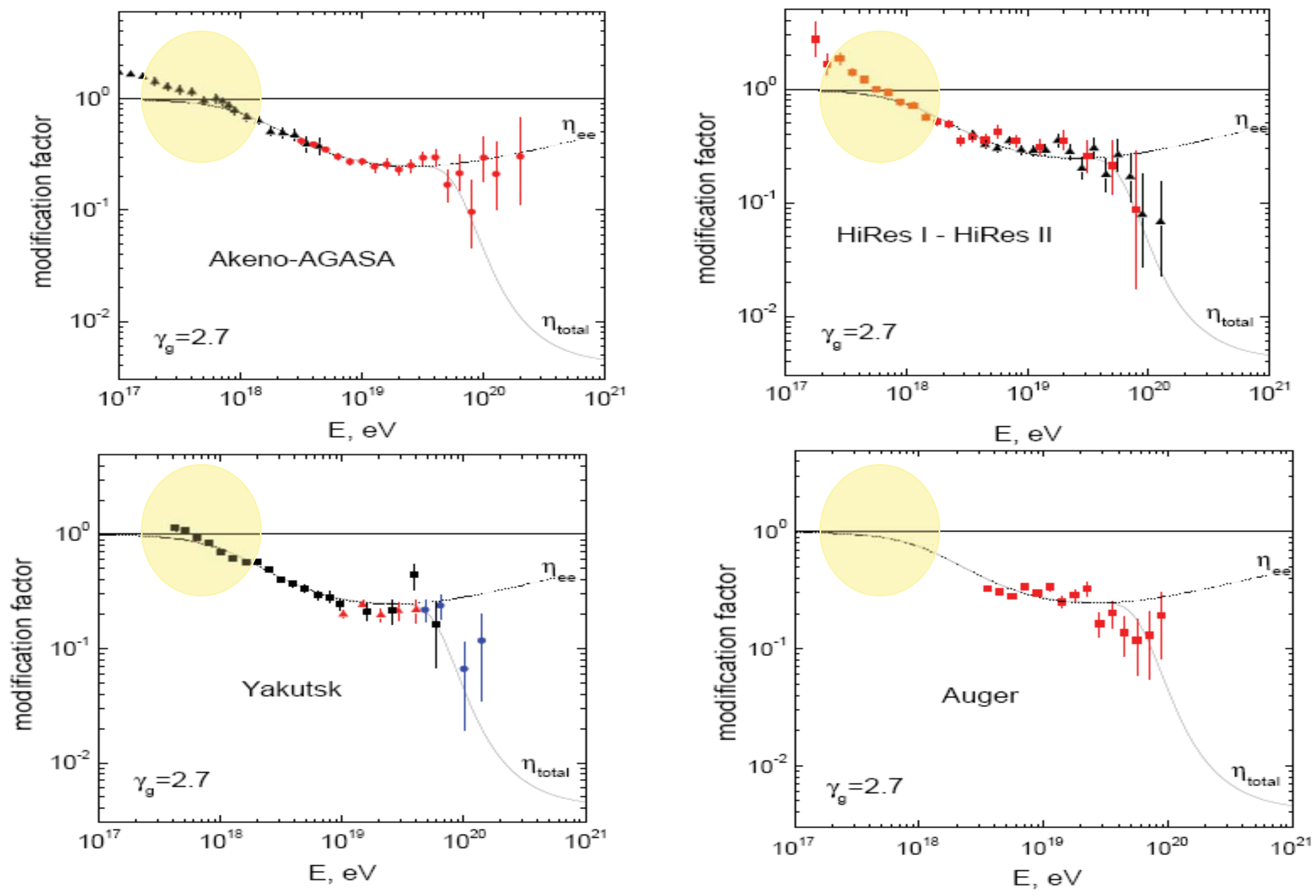


$$\eta(E) = \frac{J_p(E)}{J_p^{\mathrm{unm}}(E)}$$

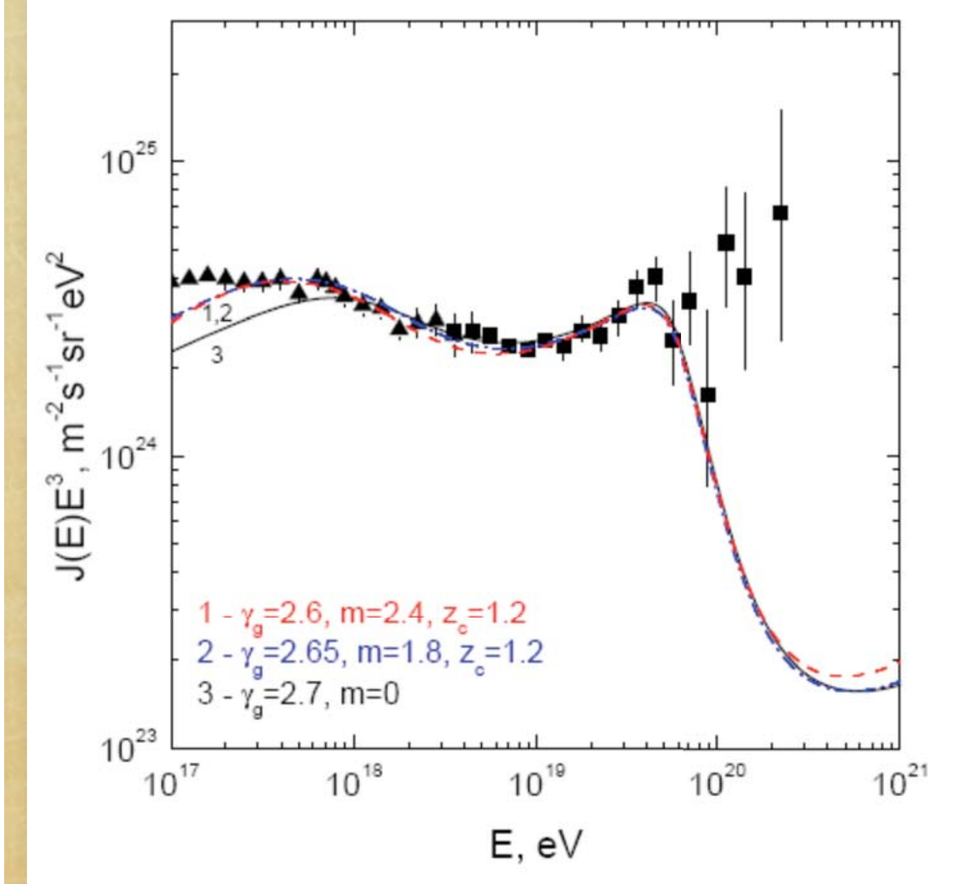
THE MODIFICATION FACTOR HAS THE ADVANTAGE OF SHOWING THE SPECTRAL MODIFICATION IN A WAY WEAKLY DEPENDENT UPON INJECTION SPECTRUM

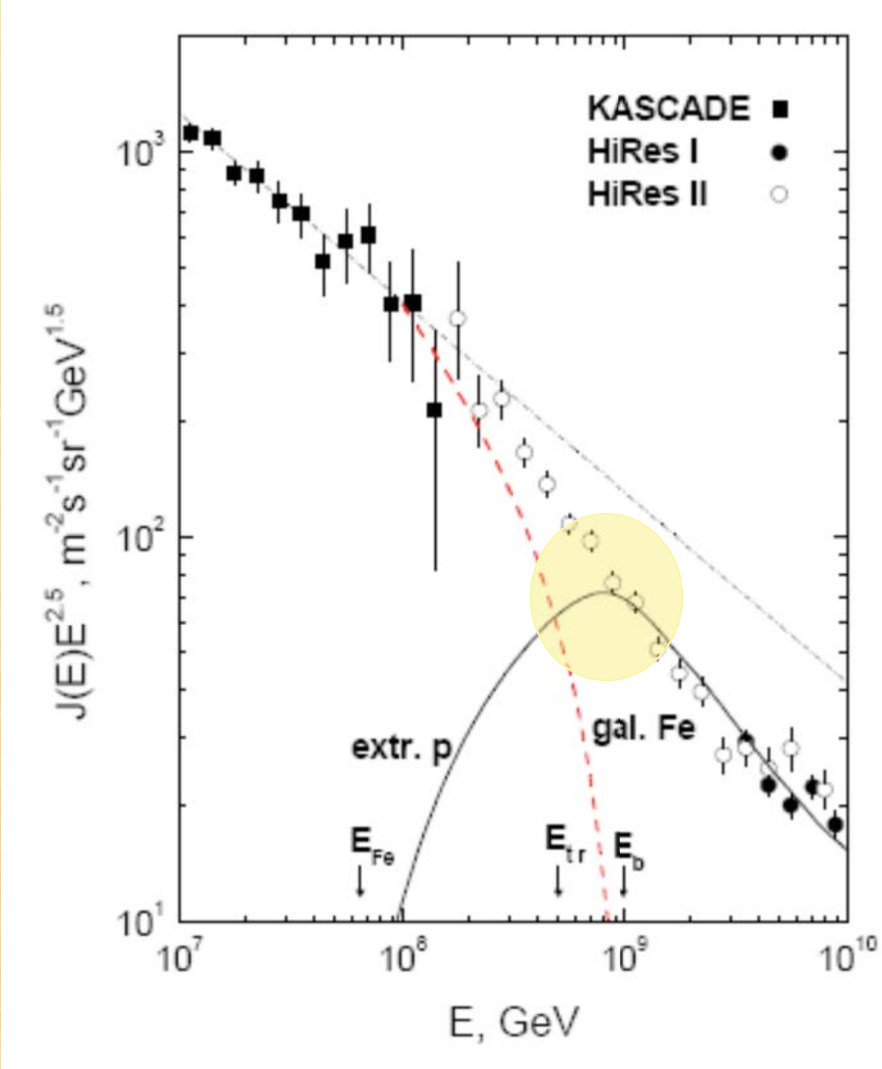
Berezinsky et al. 2005
Aloisio et al. 2007

BACK TO THE MODIFICATION FACTOR



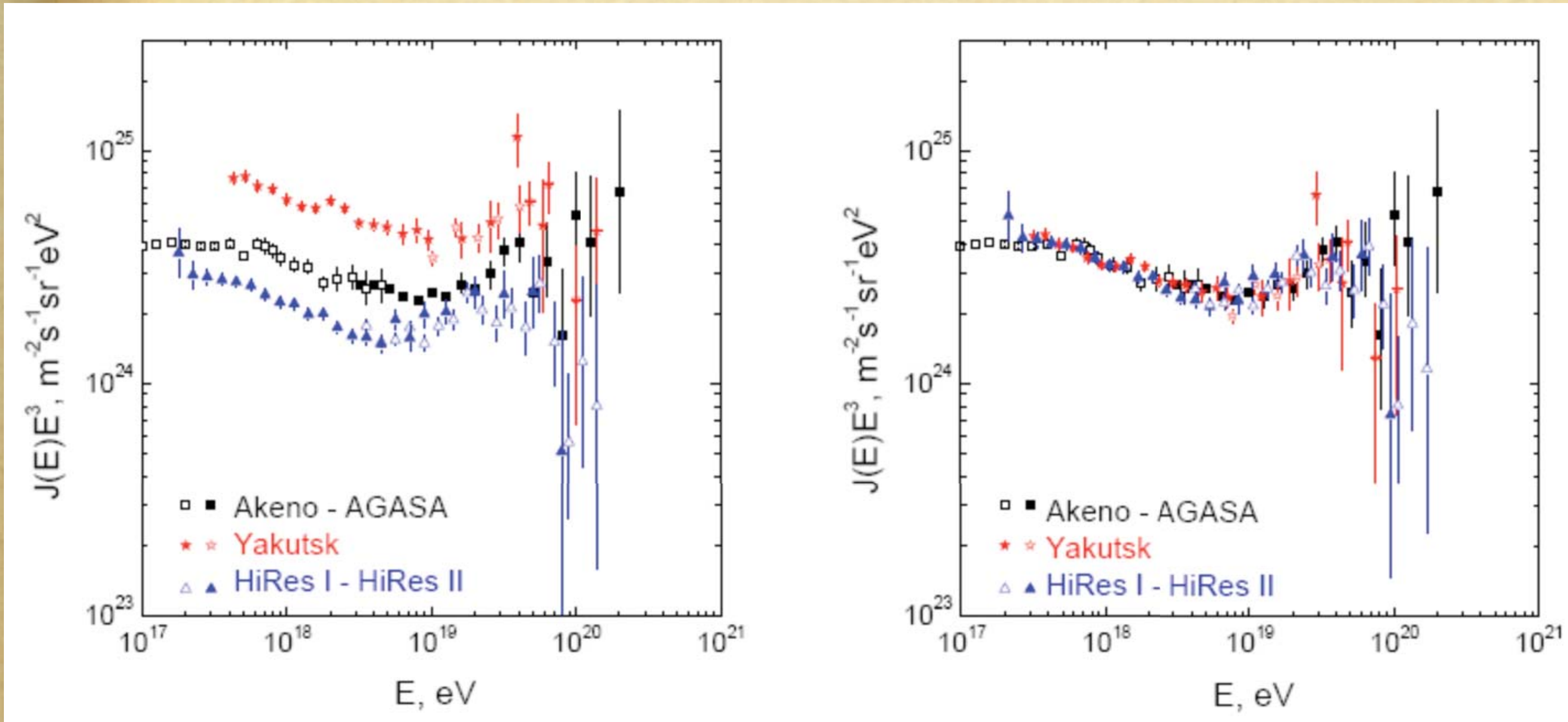
HOW DOES THE SPECTRUM LOOK LIKE? THE DIP





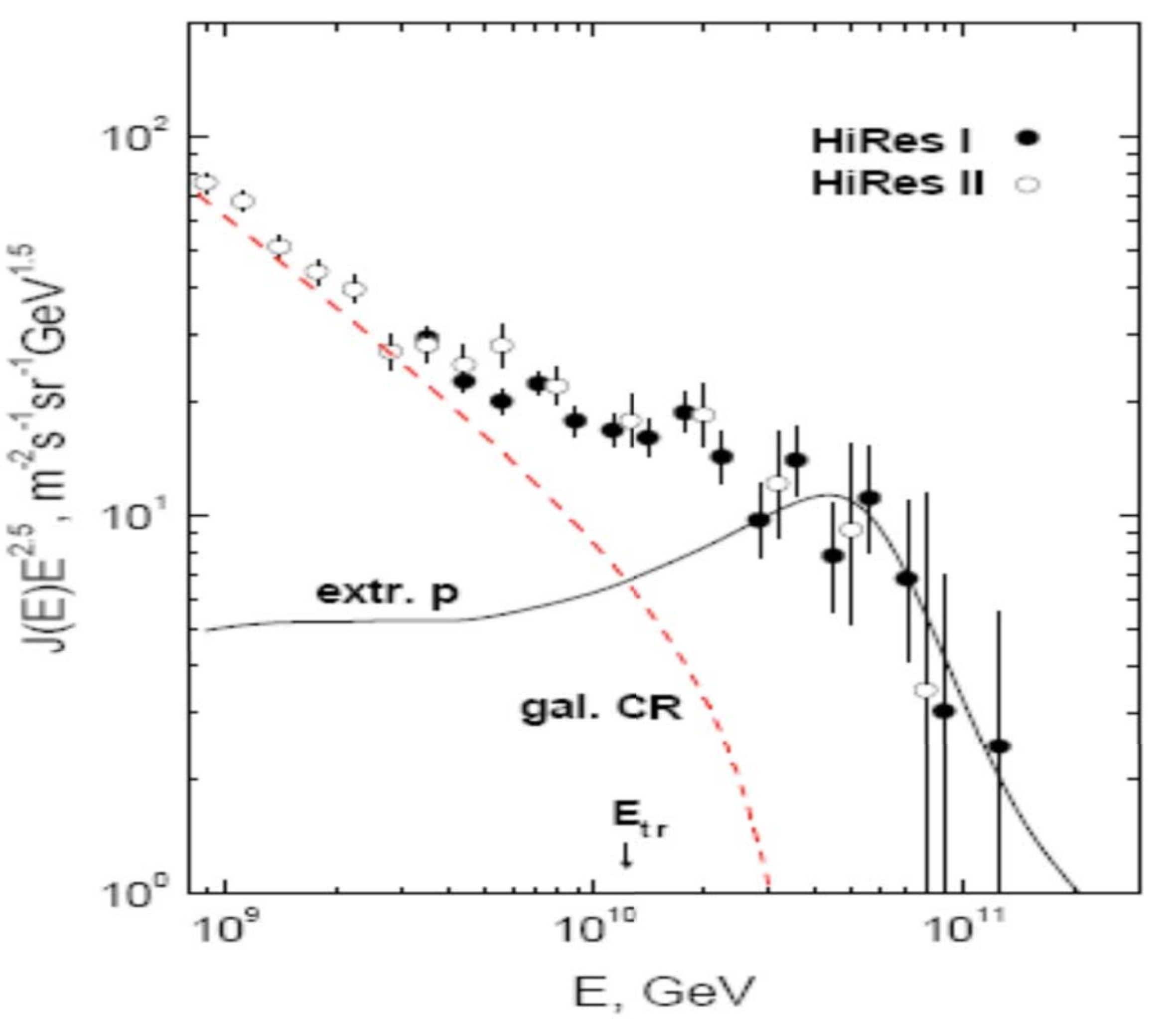
Berezinsky et al. 2005
Aloisio et al. 2007

ACCIDENT OR PHYSICS?

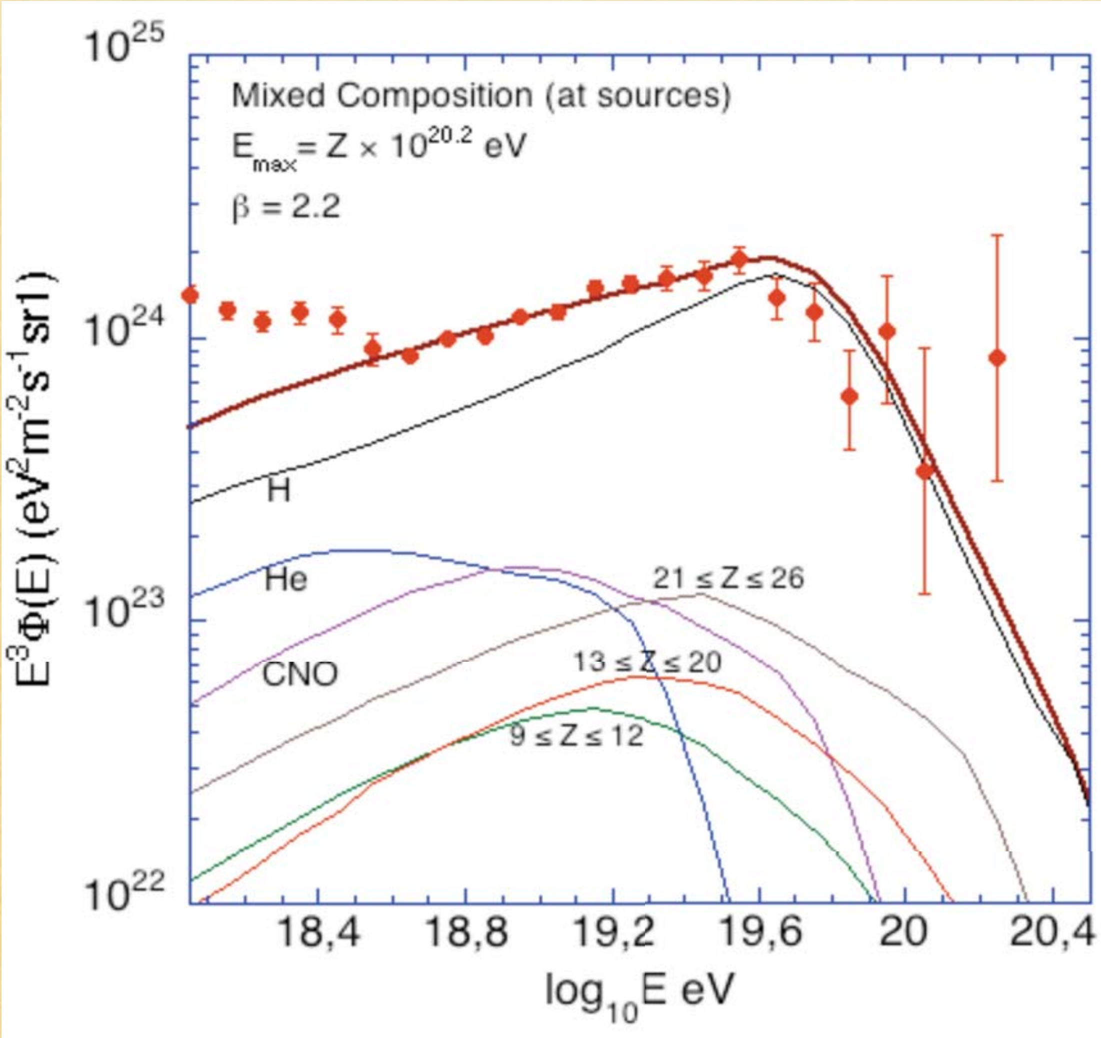


Berezinsky et al. 2005
Aloisio et al. 2007

ALTERNATIVE INTERPRETATION OF THE TRANSITION: THE ANKLE



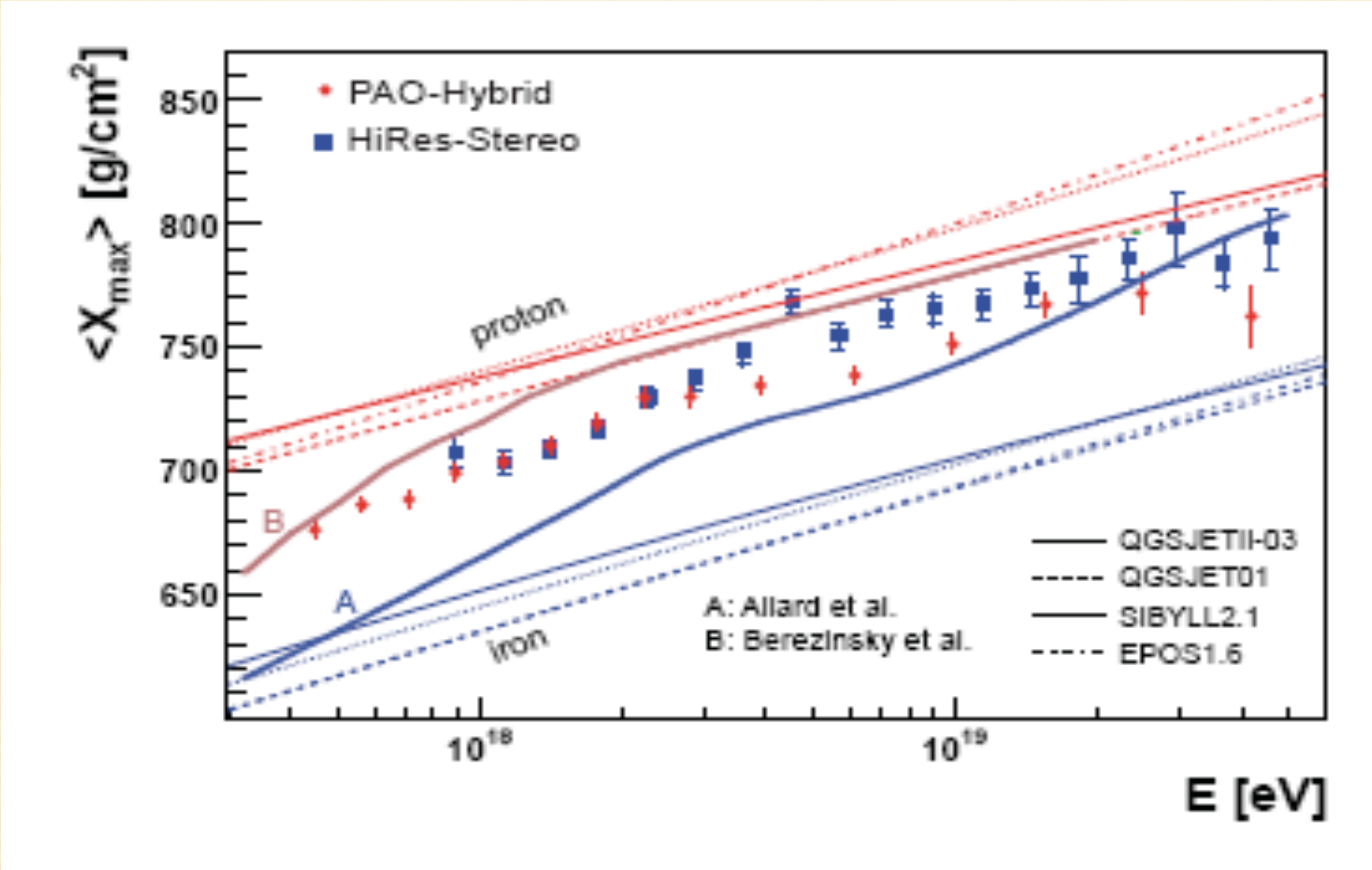
ALTERNATIVE INTERPRETATION OF THE TRANSITION: MIXED COMPOSITION



Allard et al. 2005-2008

UNDERSTANDING THE DIFFERENCE:

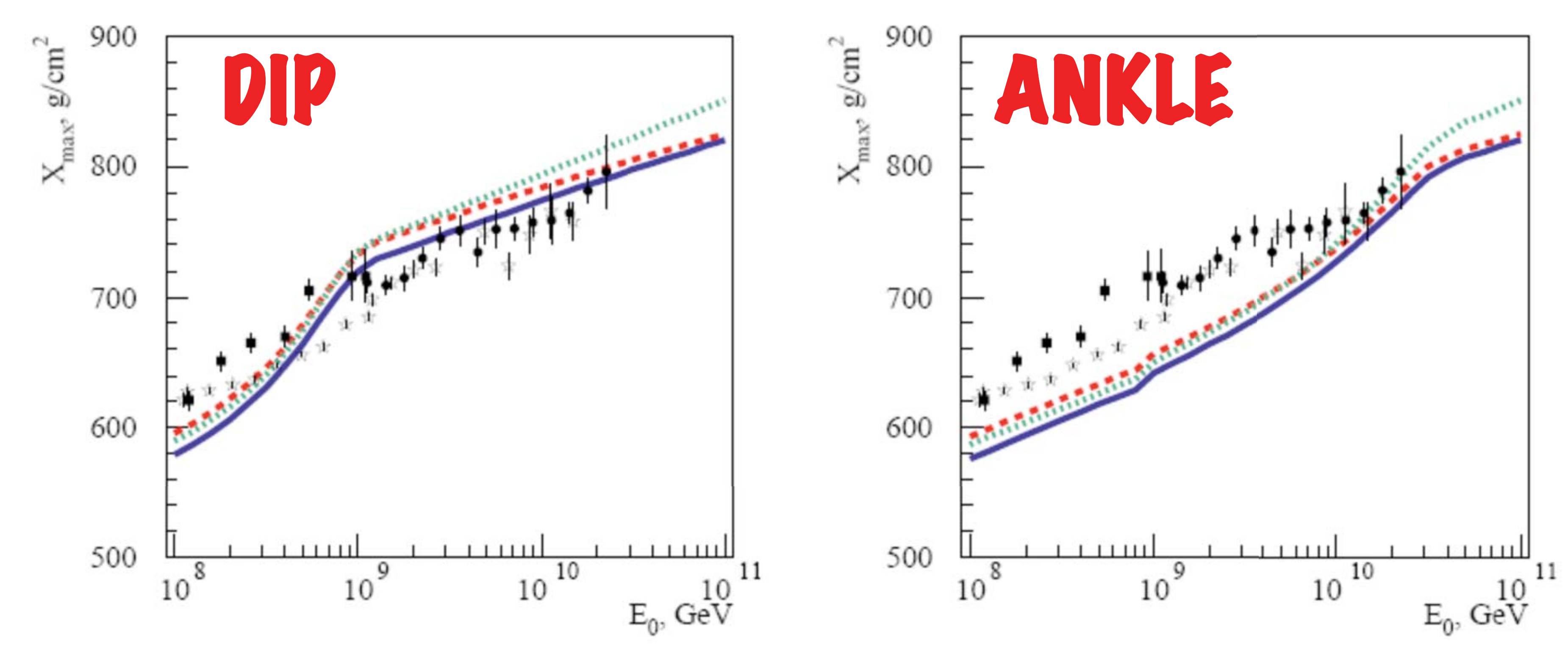
DIP VS MIXED



From Kampert 2008

UNDERSTANDING THE DIFFERENCE:

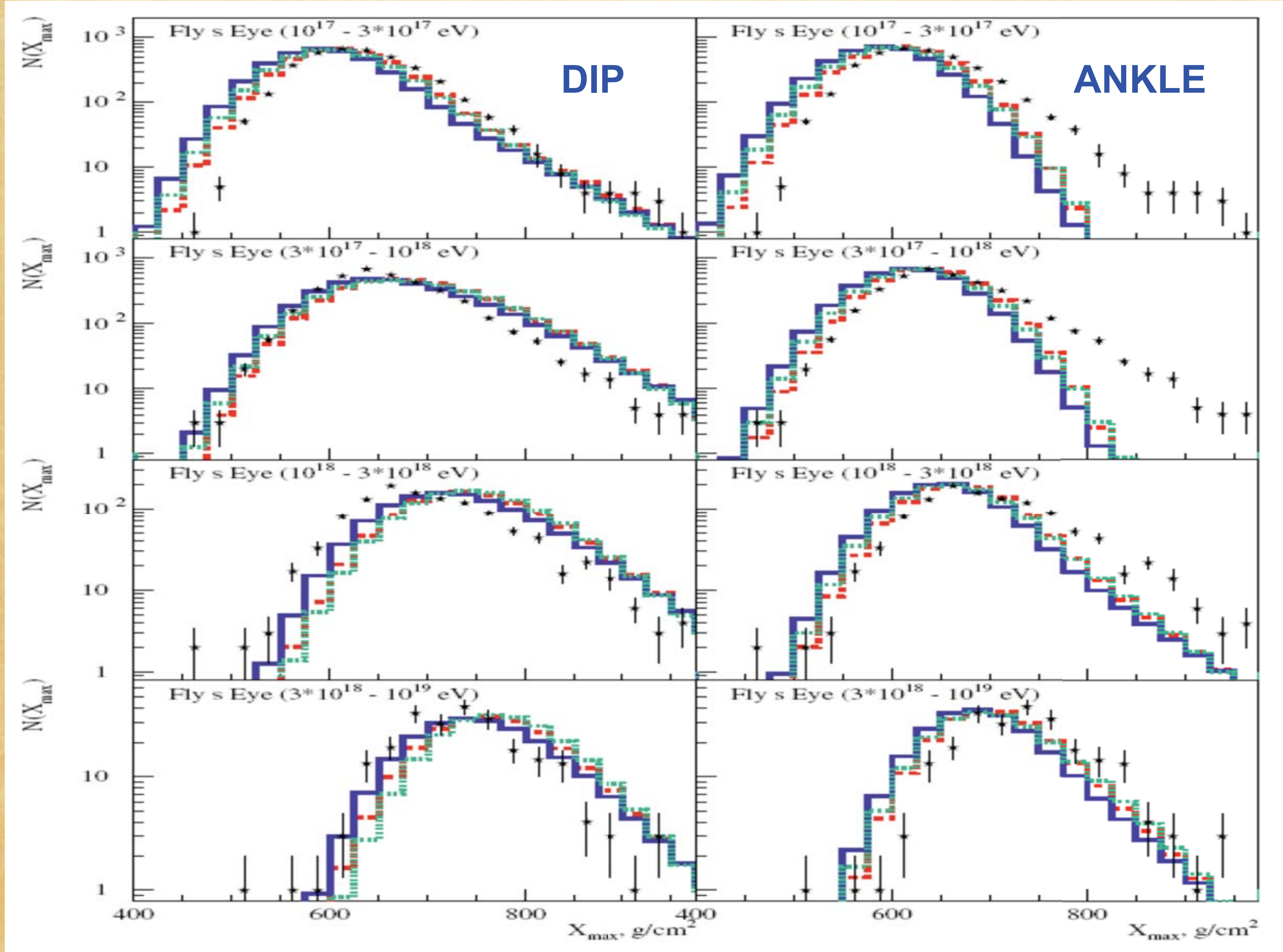
DIP VS ANKLE



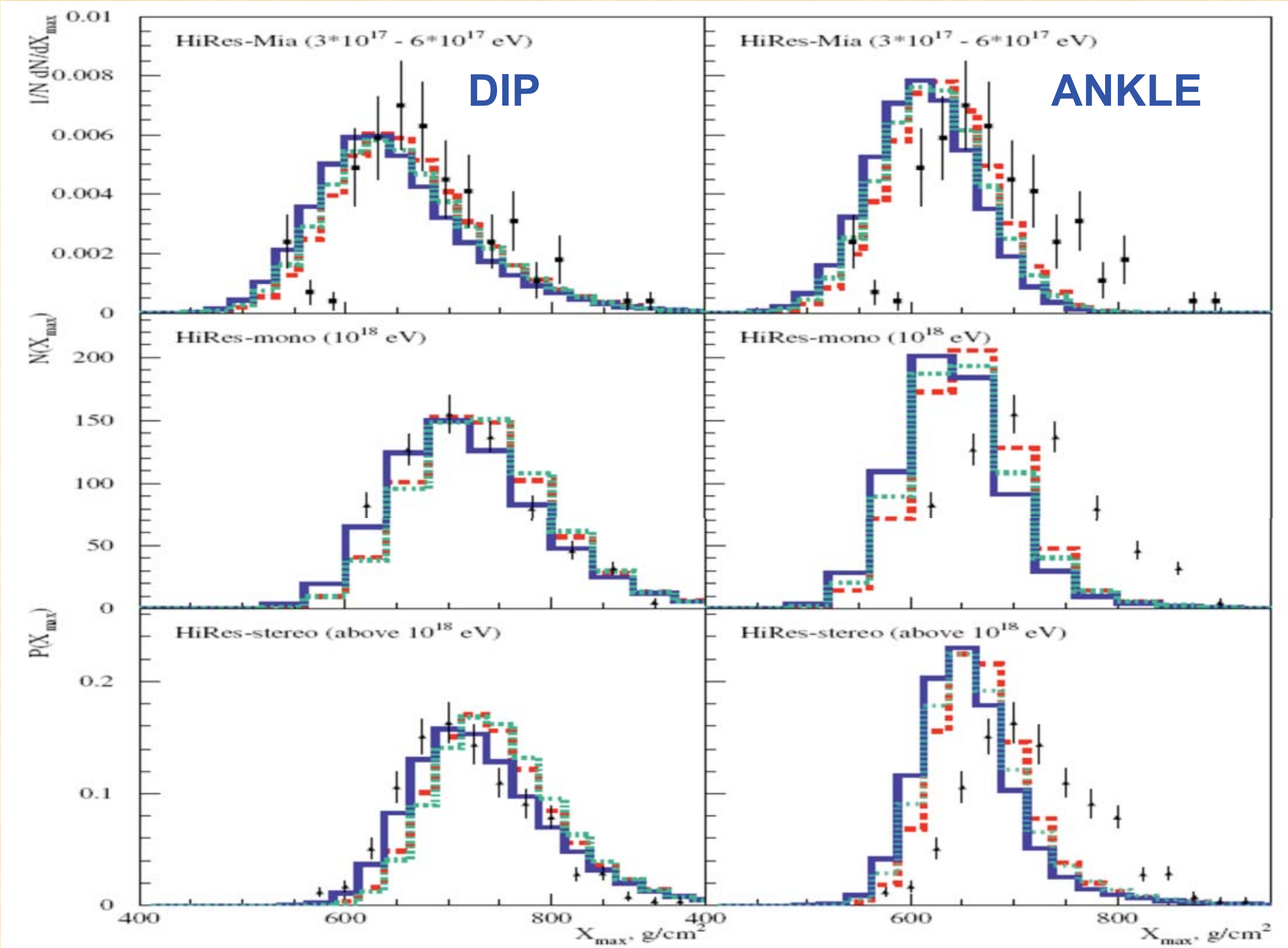
Aloisio, Berezinsky, PB & Ostapchenko 2008

THE RMS OF X_{MAX}

Aloisio, Berezinsky, PB & Ostapchenko 2008

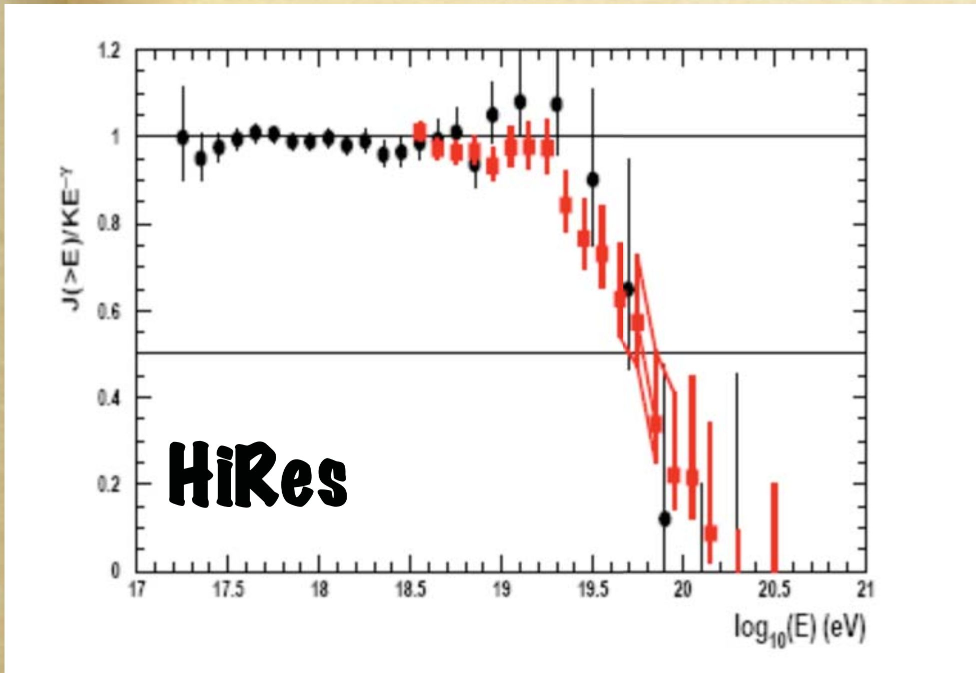


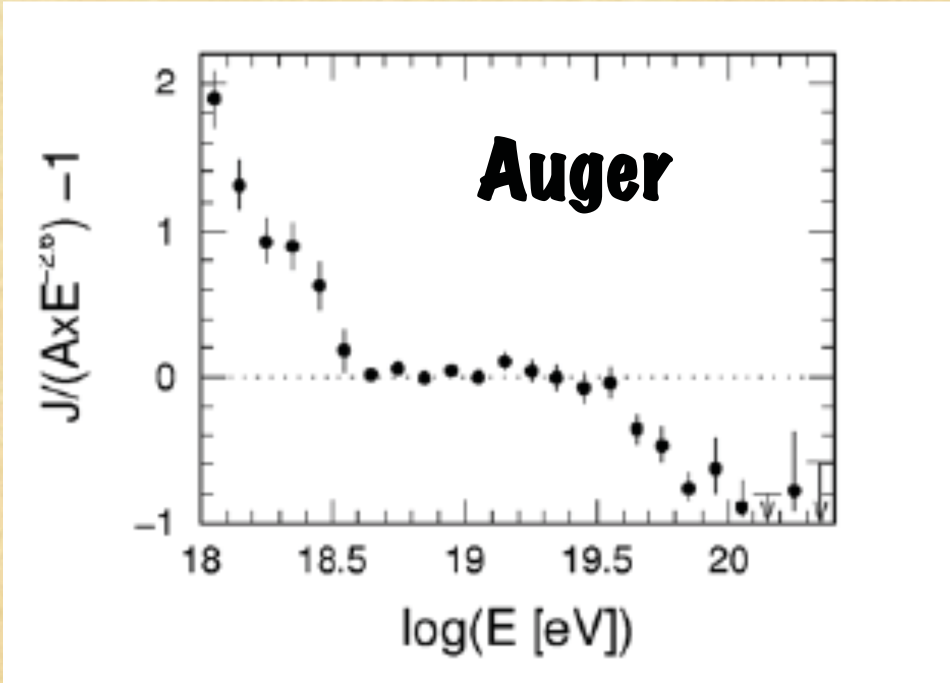
THE RMS OF X_{MAX}



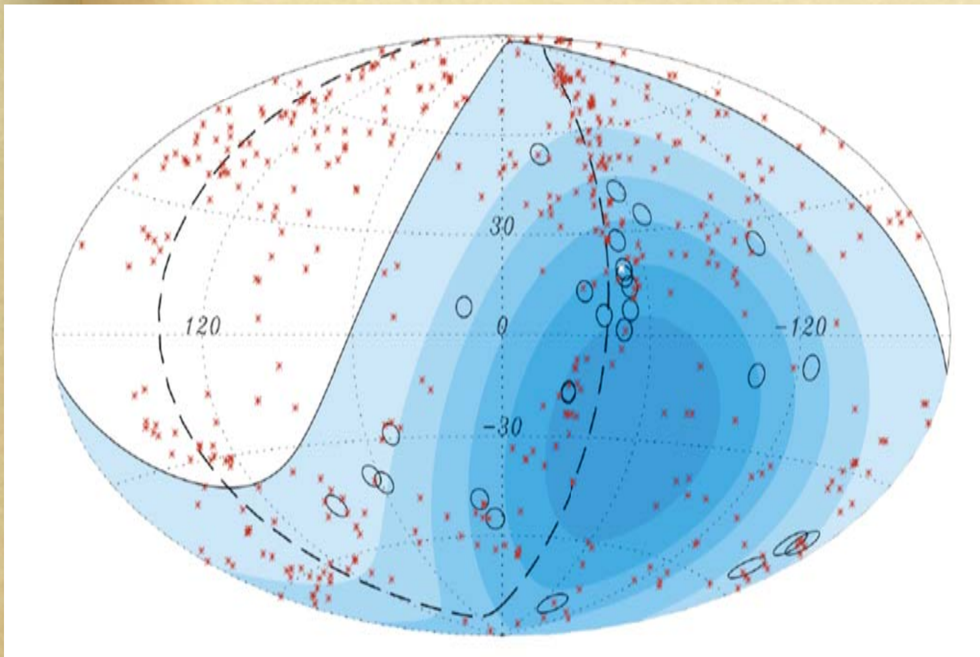
Aloisio et al. 2008

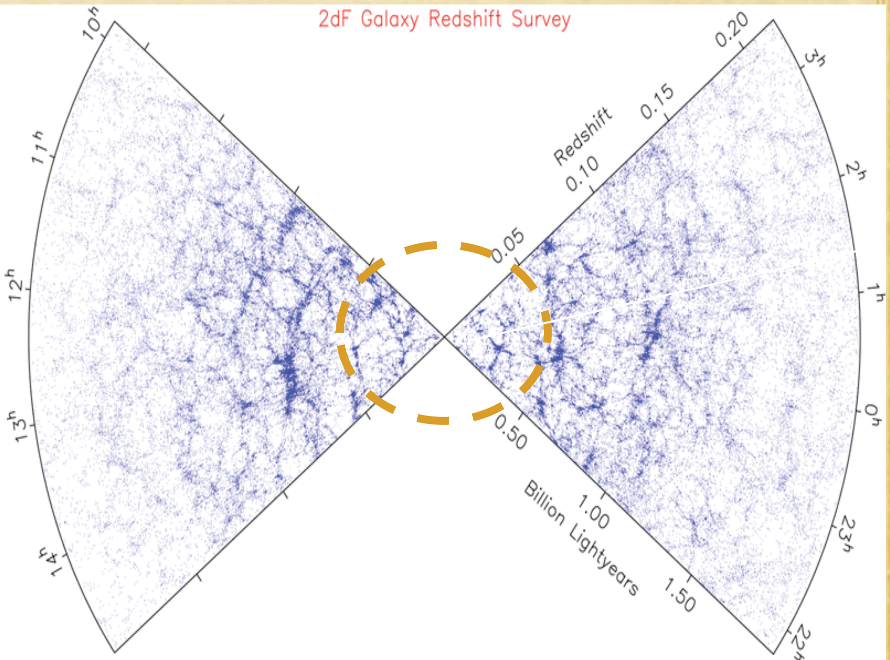
THE GZK FEATURE





CR Astronomy with PAO





CORRELATION OF THE ARRIVAL DIRECTIONS WITH THE *LOCAL DISTRIBUTION OF MATTER*

FIRST DETECTION OF ANISOTROPIES !!!

SOME INCONSISTENCIES

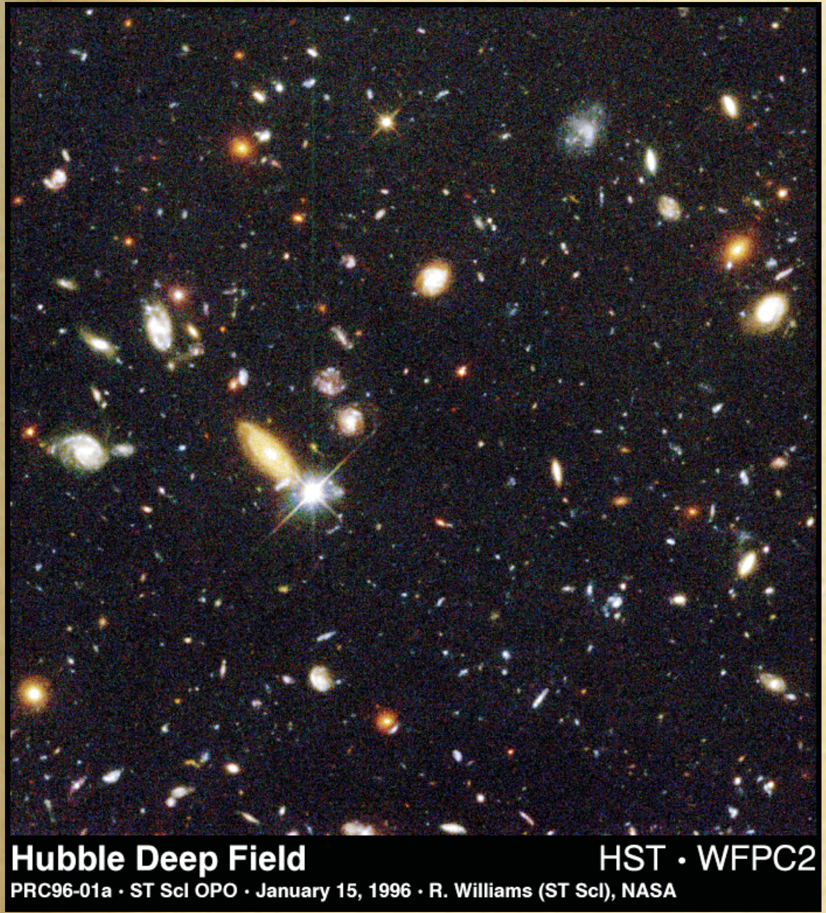
1. PAO hints to a gradually heavier composition @ high E
2. ...BUT THE GALACTIC B-FIELD → LARGE DEFLECTIONS
3. WOULD THIS KEEP THE LARGE SCALE ANISOTROPY?
4. EVEN MOST MIXED COMPOSITION MODELS DO PREDICT A LIGHT COMPOSITION AT HIGH E

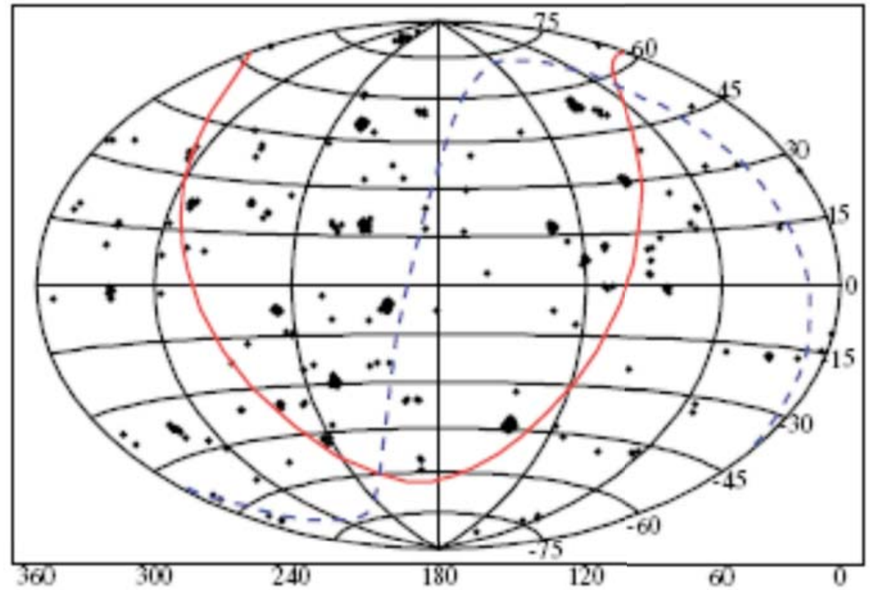
HOW DO WE 'SEE' THE SOURCES?

1. INCREASE THE STATISTICS (PAO NORTH AND/OR EUSO-LIKE)

2. SEARCH FOR SECONDARY EFFECTS
   a) EM CASCADES FROM SOURCES
   b) FIRST GENERATION PHOTONS FROM NEARBY SOURCES
   c) RADIATION FROM FIRST GENERATION ELECTRONS

A New type of Astrophysics



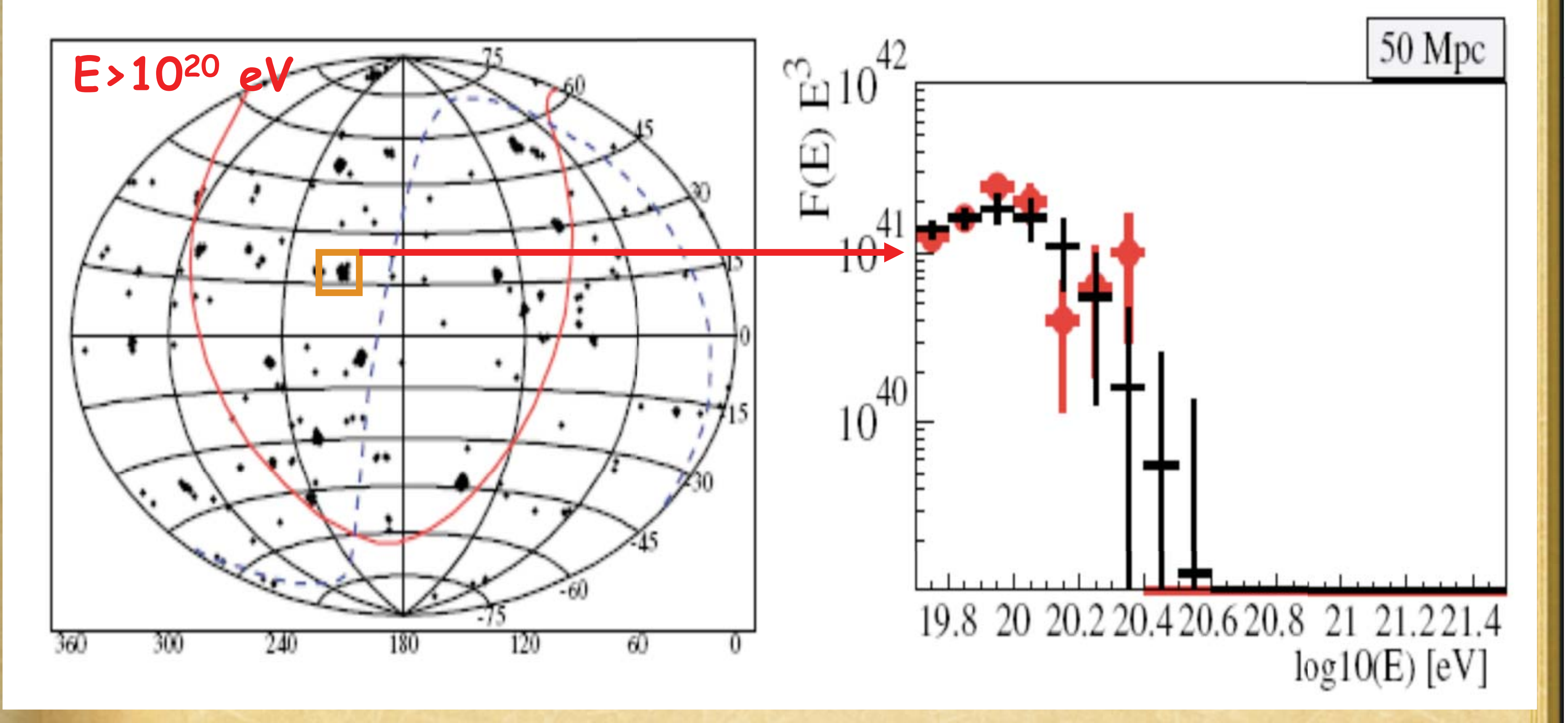


PB & De Marco 2003

CRITICAL EXPOSURE

$$\Sigma_{exp} > \Sigma_c = 42000\ \rho_{-5}\ \mathrm{km}^2\ \mathrm{sr\ yr}$$

...MEASURE THE INJECTION SPECTRUM FROM ONE SOURCE...

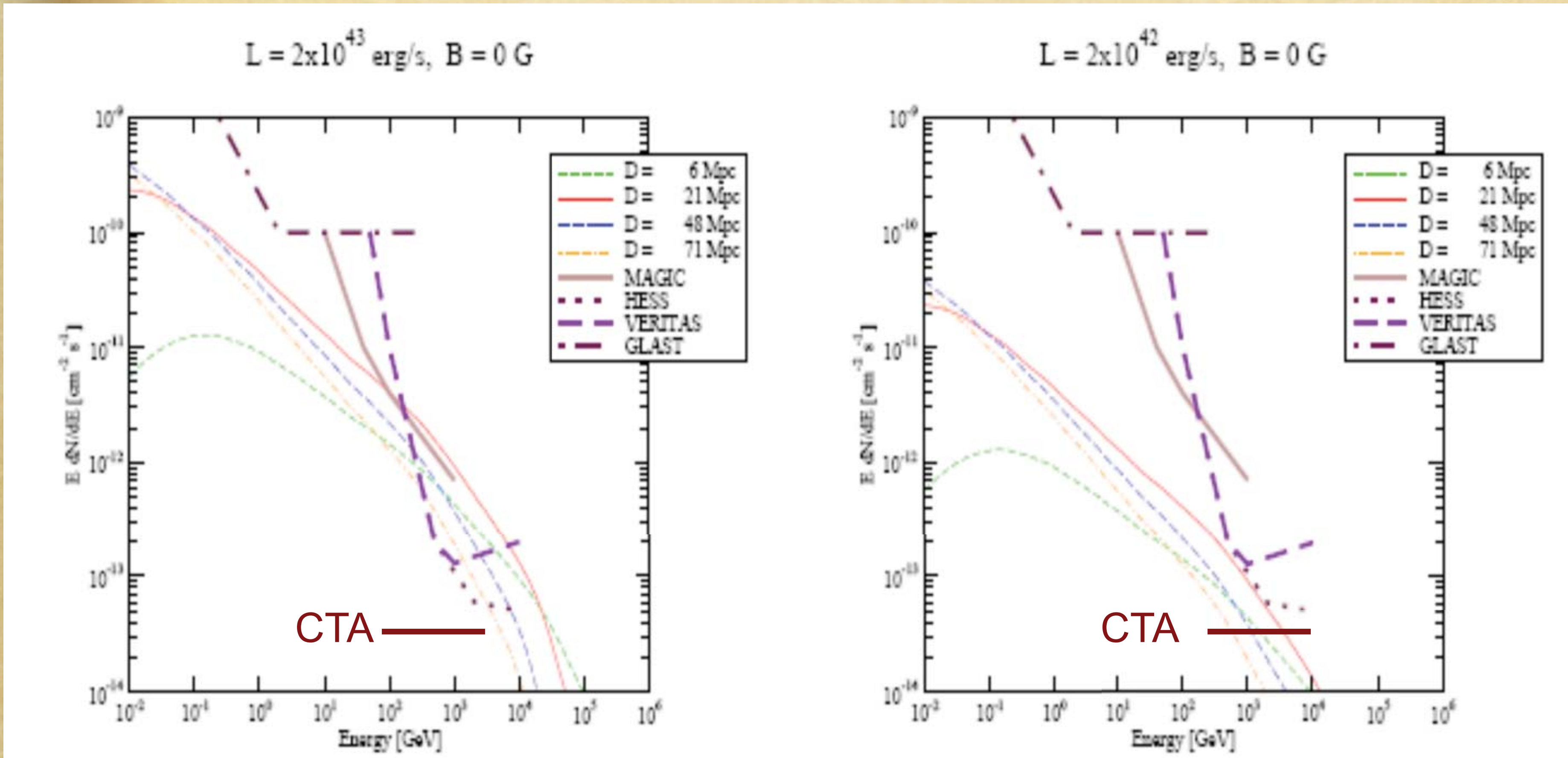


PB & De Marco 2003

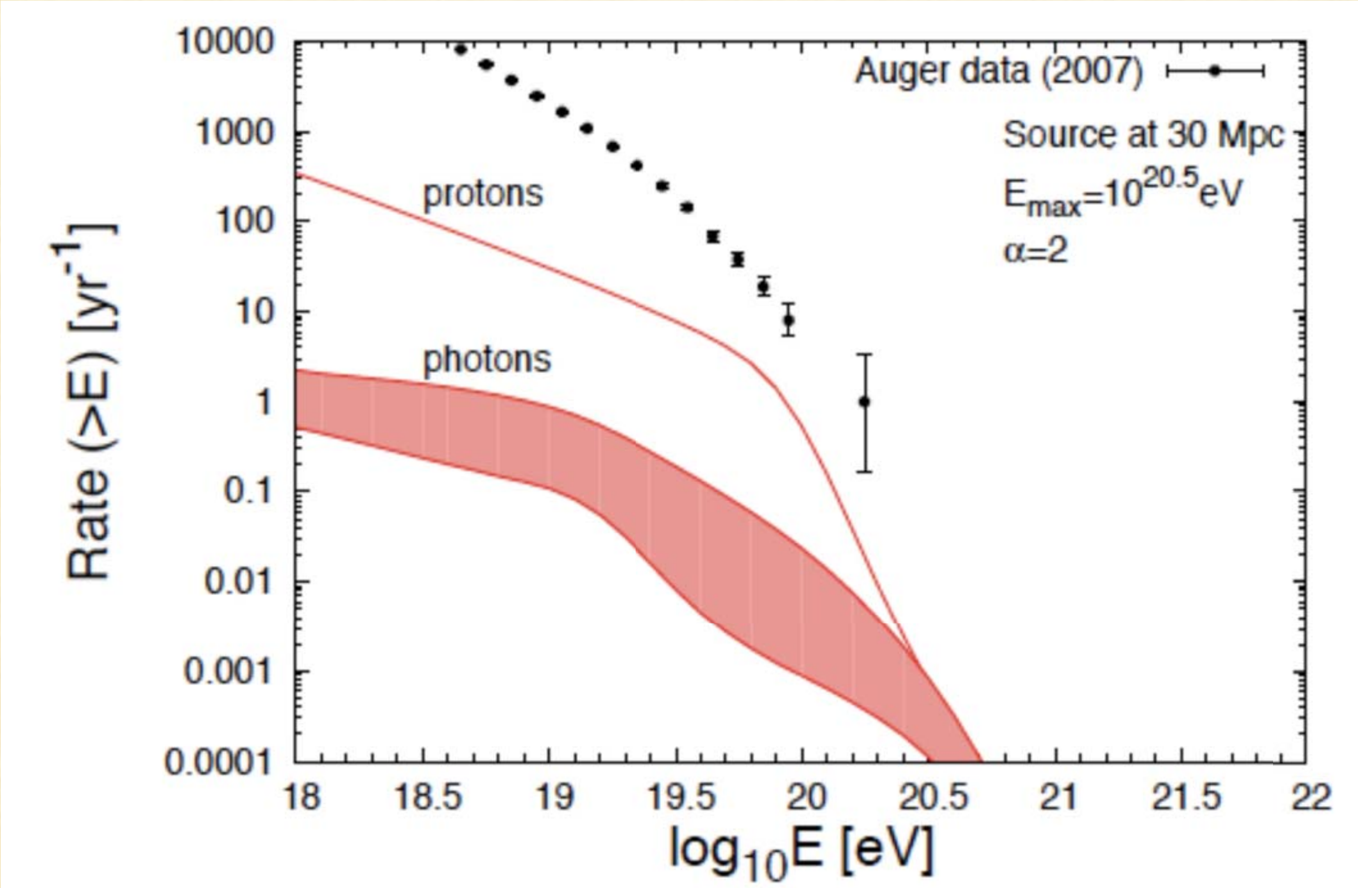
EM CASCADES FROM SOURCES

Source → **Electromagnetic cascade**

Ferrigno, PB & De Marco 2005
Gabici & Aharonian 2007

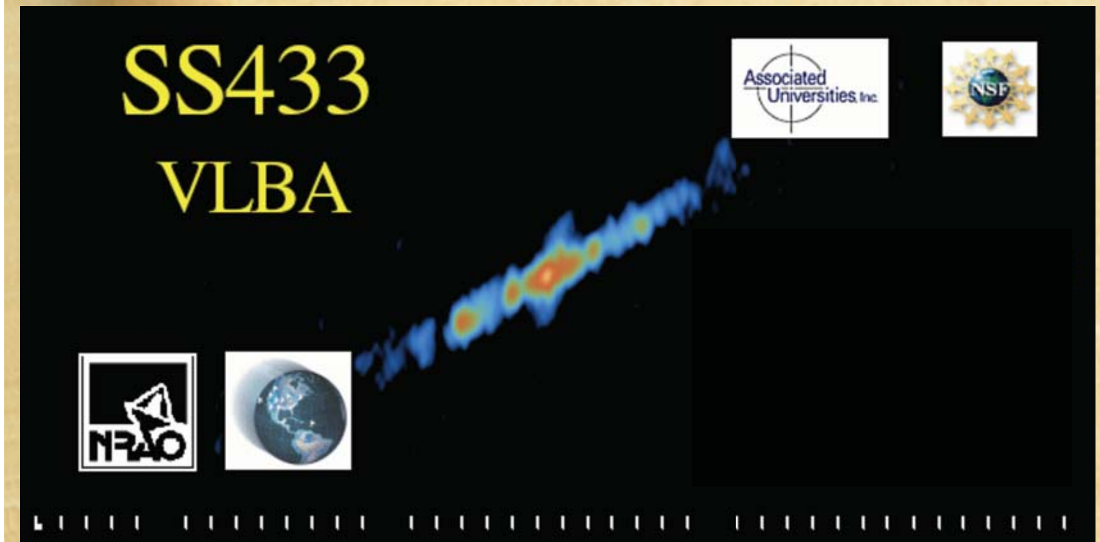


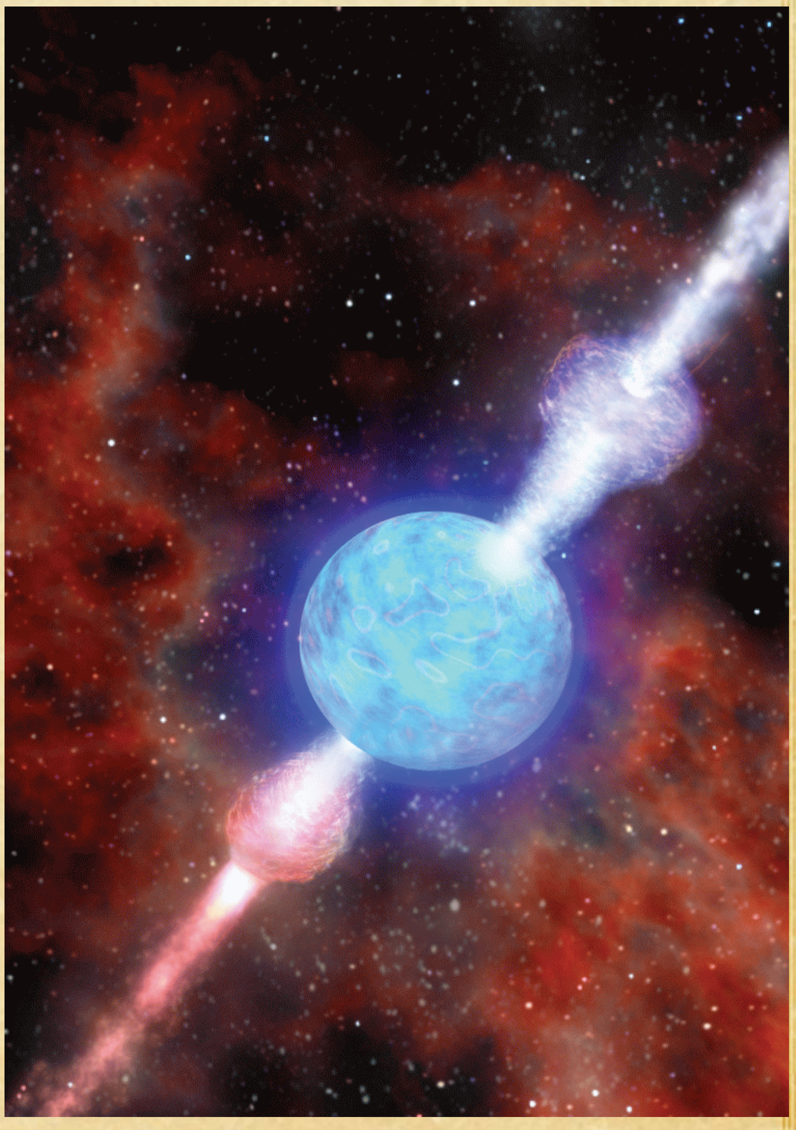
FIRST GENERATION g AND e



Taylor, Hinton, Pb & Ave, 2009

SOME BASIC ASPECTS OF PARTICLE ACCELERATION AT RELATIVISTIC SHOCKS





BASICS OF ACCELERATION AT RELATIVISTIC SHOCKS

$$\gamma_1\beta_1 n_1 = \gamma_2\beta_2 n_2$$

$$\gamma_1^2\beta_1(\varepsilon_1 + p_1) = \gamma_2^2\beta_2(\varepsilon_2 + p_2)$$

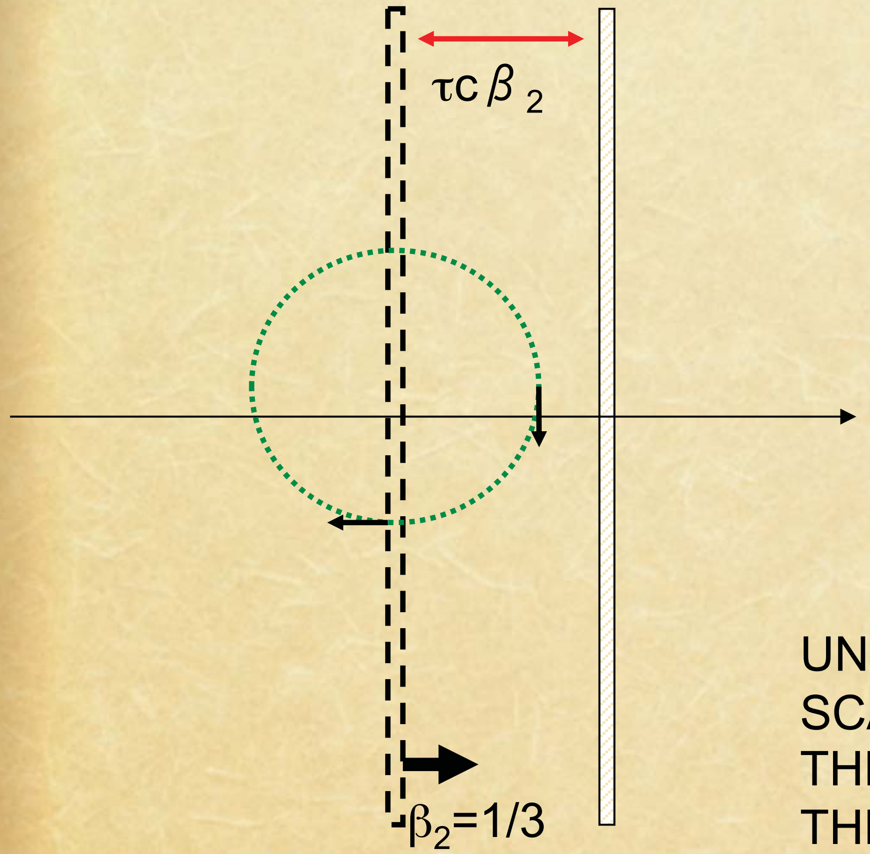
$$\gamma_1^2\beta_1^2(\varepsilon_1 + p_1) + p_1 = \gamma_2^2\beta_2^2(\varepsilon_2 + p_2) + p_2$$

IN THE ASSUMPTION THAT:

$\frac{B_1^2}{4\pi} << (\varepsilon_1 + p_1)$	$\gamma_1 >> 1$	$p_1 = 0$
No equipartition	ultrarelativistic	pressureless

WE FIND THAT:

$$p_2 = \frac{1}{3}\varepsilon_2 \qquad \beta_2 = \frac{1}{3}$$



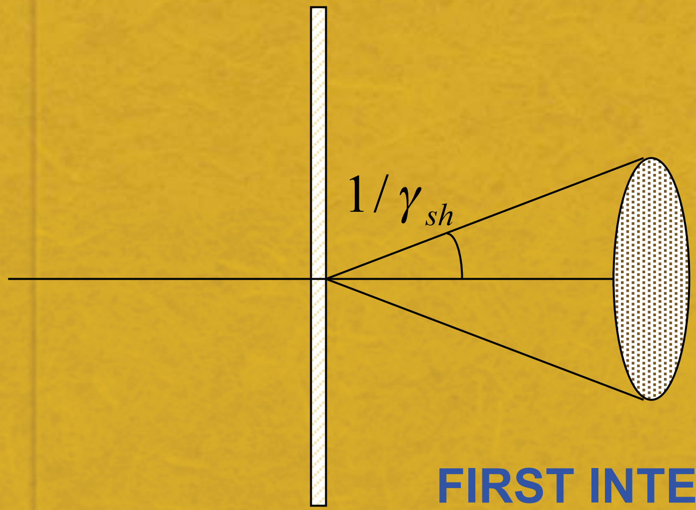
$$\tau \approx \frac{3}{4}\frac{2\pi\, r_L}{c}$$

$$\Delta x = \frac{1}{3} c\,\tau = \frac{\pi}{2} r_L > r_L$$

UNLESS THERE IS STRONG SCATTERING DOWSNTREAM THE PARTICLES ARE TRAPPED THERE

THE RETURN PROBABILITY FROM DOWNSTREAM IS EXPECTED TO BE SMALLER THAN FOR NEWTONIAN SHOCKS: STEEPER SPECTRA

ANISOTROPY



$$\delta\mu = \left[-1 + \frac{1+3\beta_{rel}}{3+\beta_{rel}}\right] \approx \frac{1}{4}\frac{1}{\gamma_{rel}^2}$$

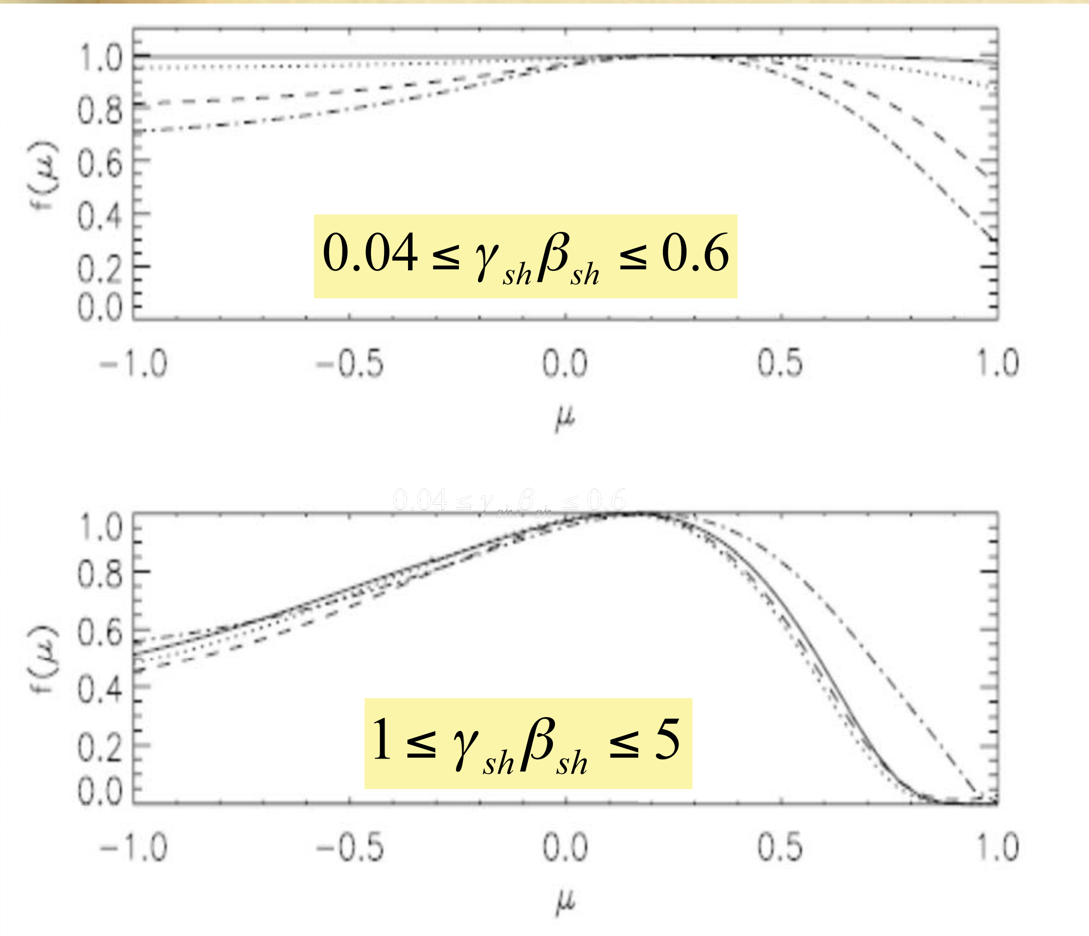
FIRST INTERACTION:

$$E_i \Rightarrow E_d = \gamma_{rel} E_i (1+\beta_{rel}) \Rightarrow E_f = \gamma_{rel}^2 E_i (1+\beta_{rel})^2 \approx 4\gamma_{rel}^2 E_i$$

FURTHER INTERACTIONS:

$$E_f \approx 2\, E_i$$

EFFECTS OF ANISOTROPY



Particle Slopes for Shocks in the SPAS Limit

$\gamma_{sh}\beta_{sh}$	u	u_d	Slope
0.04........................	0.04	0.01	4.00
0.2........................	0.196	0.049	3.99
0.4........................	0.371	0.094	3.99
0.6........................	0.51	0.132	3.98
1.0........................	0.707	1.191	4.00
2.0........................	0.894	0.263	4.07
4.0........................	0.97	0.305	4.12
5.0........................	0.98	0.311	4.13

PB & Vietri 2005

SOME REMARKS

- THE SPECTRUM OF ACCELERATED PARTICLES IN THE RELATIVISTIC CASE IS STILL A POWER LAW
- THE SLOPE OF THIS POWER LOW IN THE ULTRAREL CASE IS ABOUT 2.3
- HOWEVER THE SLOPE CAN BECOME APPRECIABLY HARDER (FLATTER SPECTRA) FOR LARGE ANGLE SCATTERING
- OR APPRECIABLY SOFTER (STEEP SPECTRA) DUE TO … BASICALLY ANYTHING ELSE YOU DO (FOR INSTANCE COMPRESSION OF TURBULENCE AT THE SHOCK)
- SHOCK ACCELERATION AT RELATIVISTIC SHOCKS DEPENDS ALSO ON THE EQUATION OF STATE OF THE DOWNSTREAM PLASMA (PROTONS, PAIRS, B-FIELDS ALL CHANGE THE RESULTS DRAMATICALLY)
- THERE IS NO NON LINEAR THEORY OF PARTICLE ACCELERATION AT RELATIVISTIC SHOCKS