COSMIC RAYS
above and *below* the knee

PASQUALE BLASI

INAF/Arcetri Astrophysical Observatory

OUTLINE

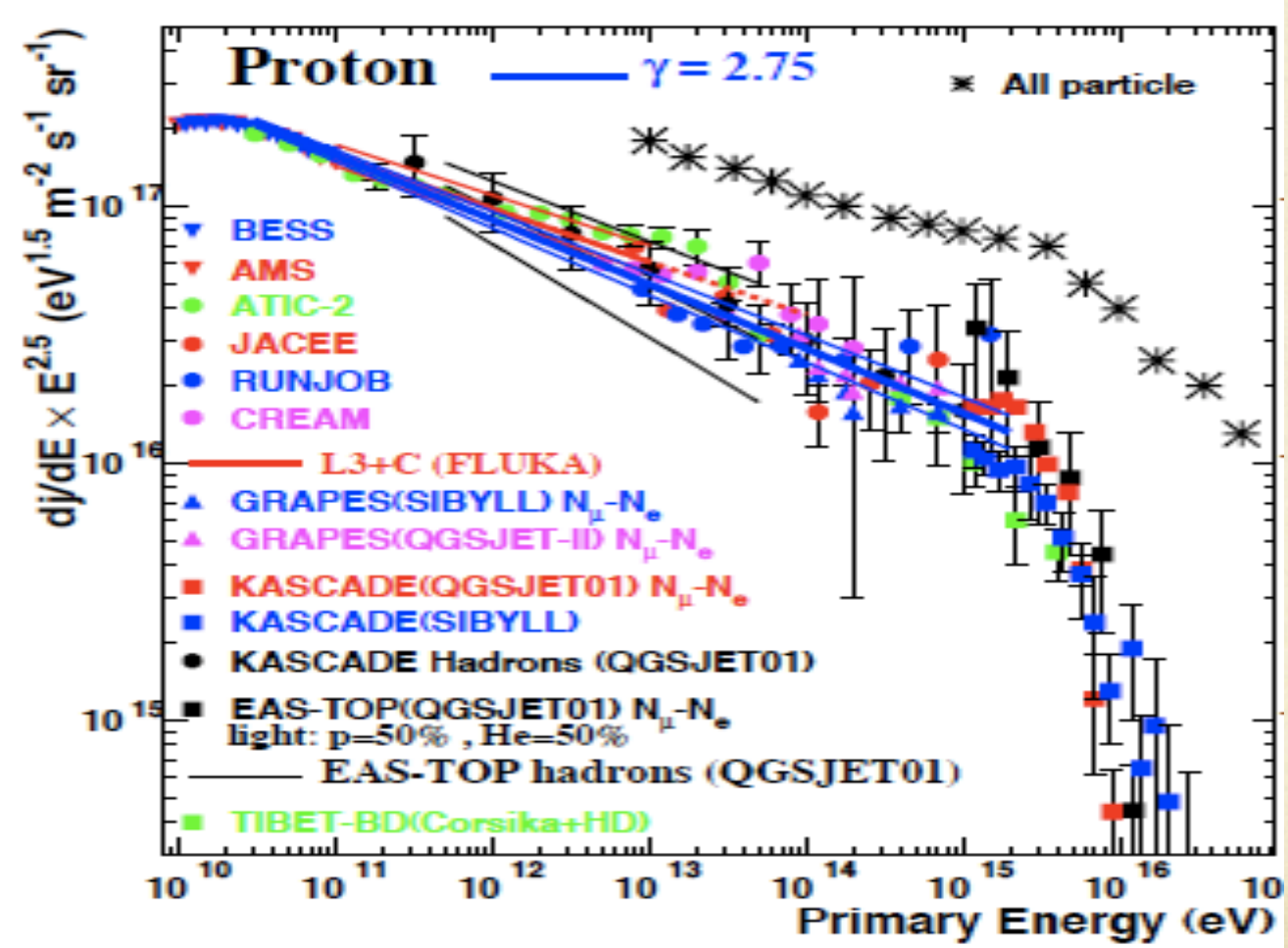
Acceleration of CR protons below the knee

The knee and its possible connection to Chemistry

The end of Galactic CRs

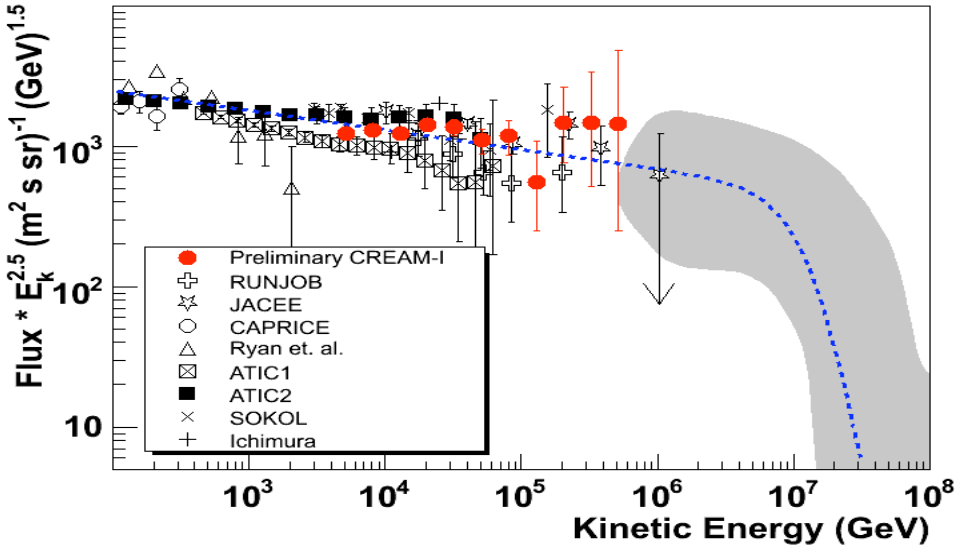
The transition to UHECRs

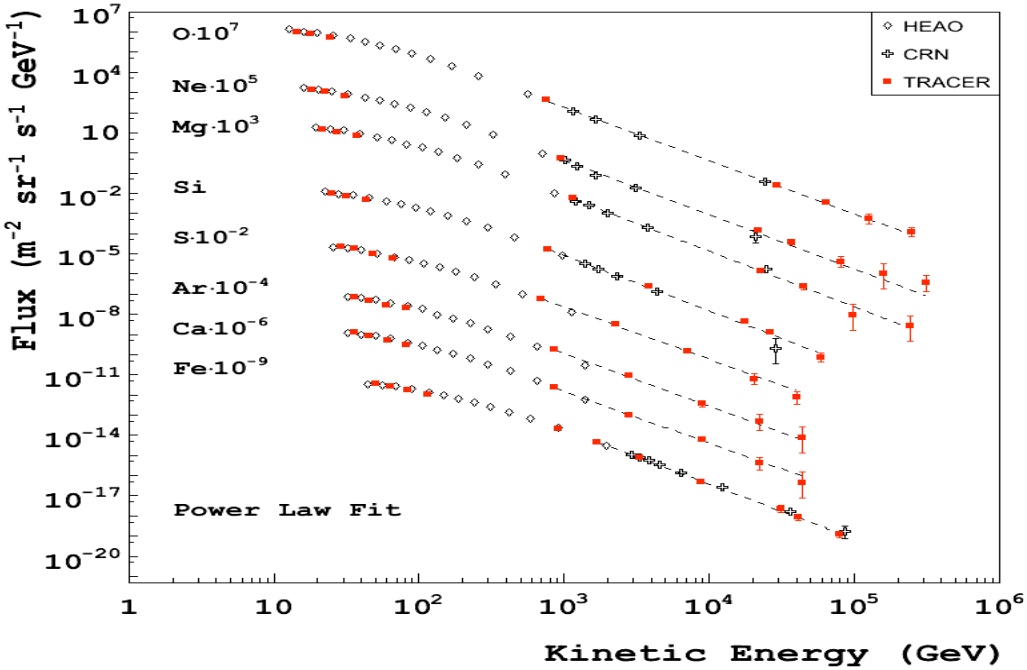
Spectrum of Protons

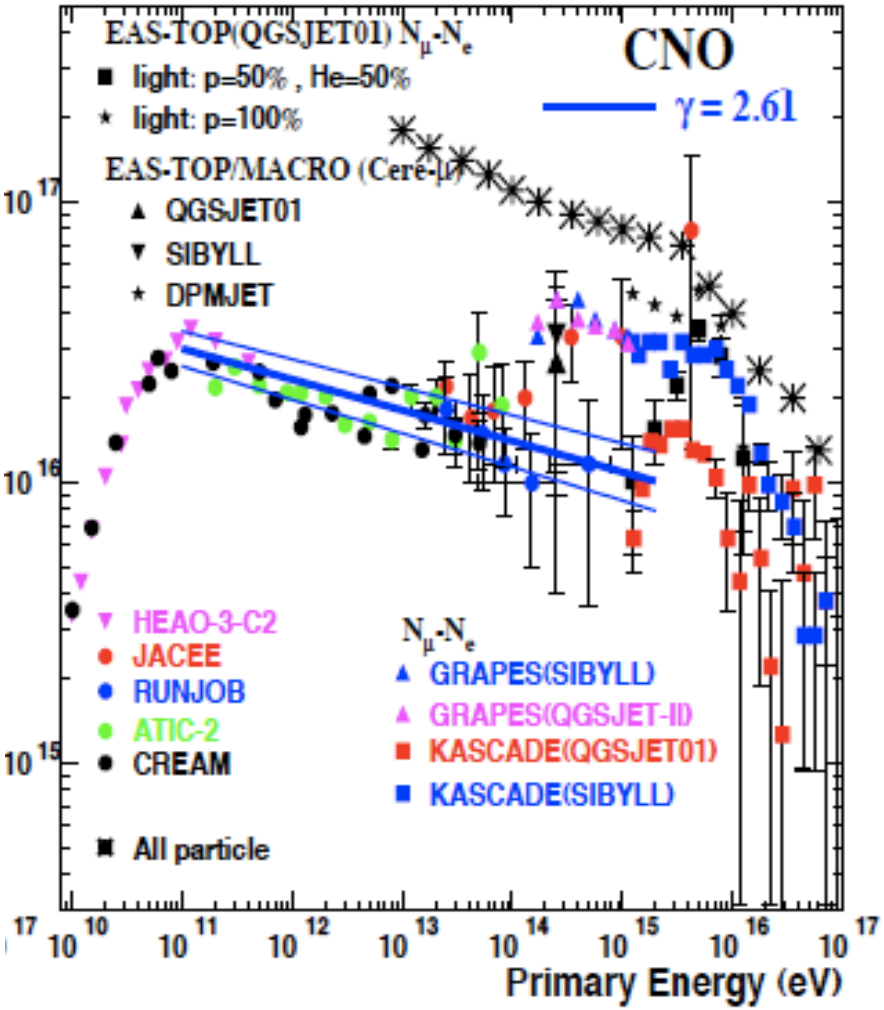


Data from Bertaina et al. 2008

Spectra of nuclei (1)

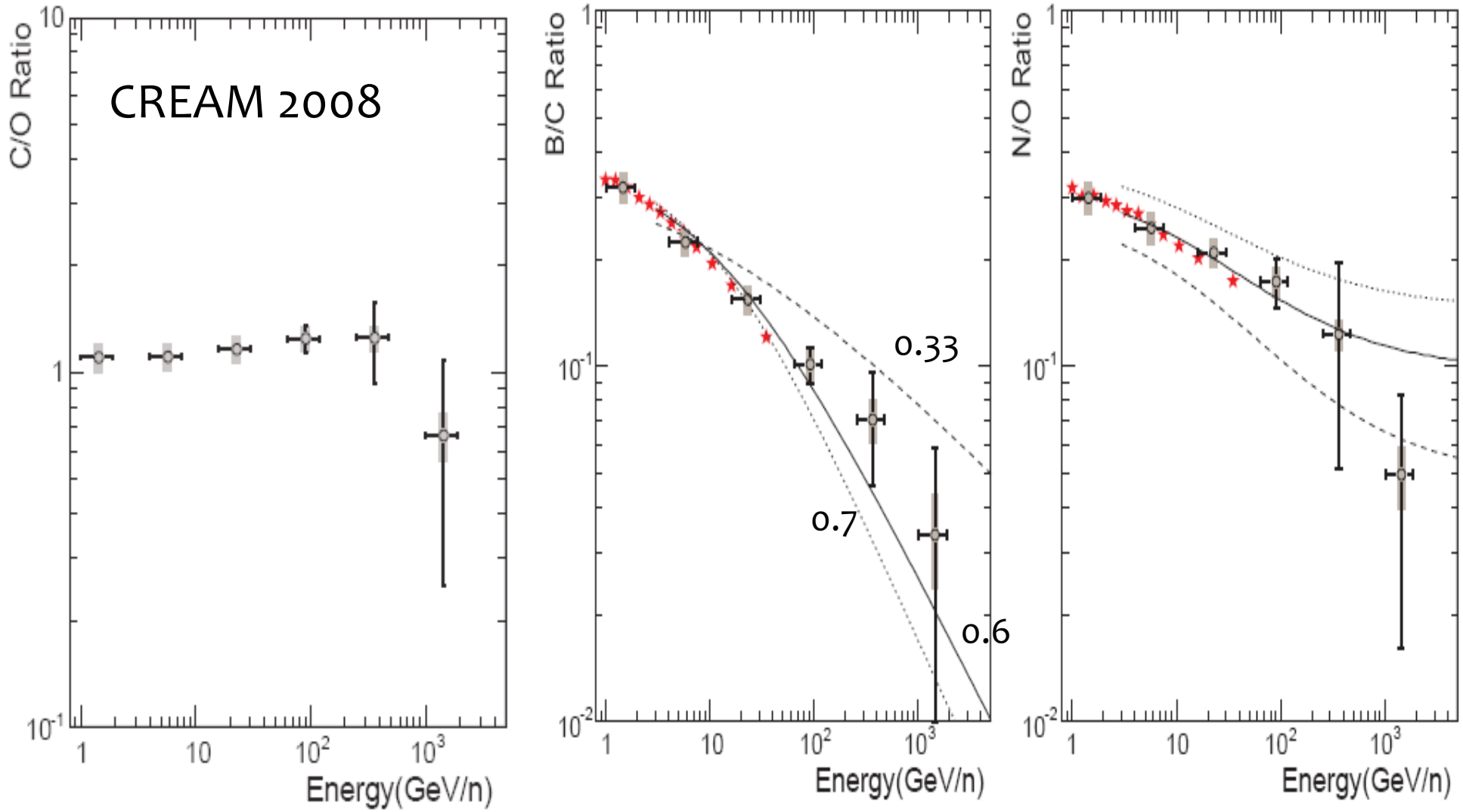




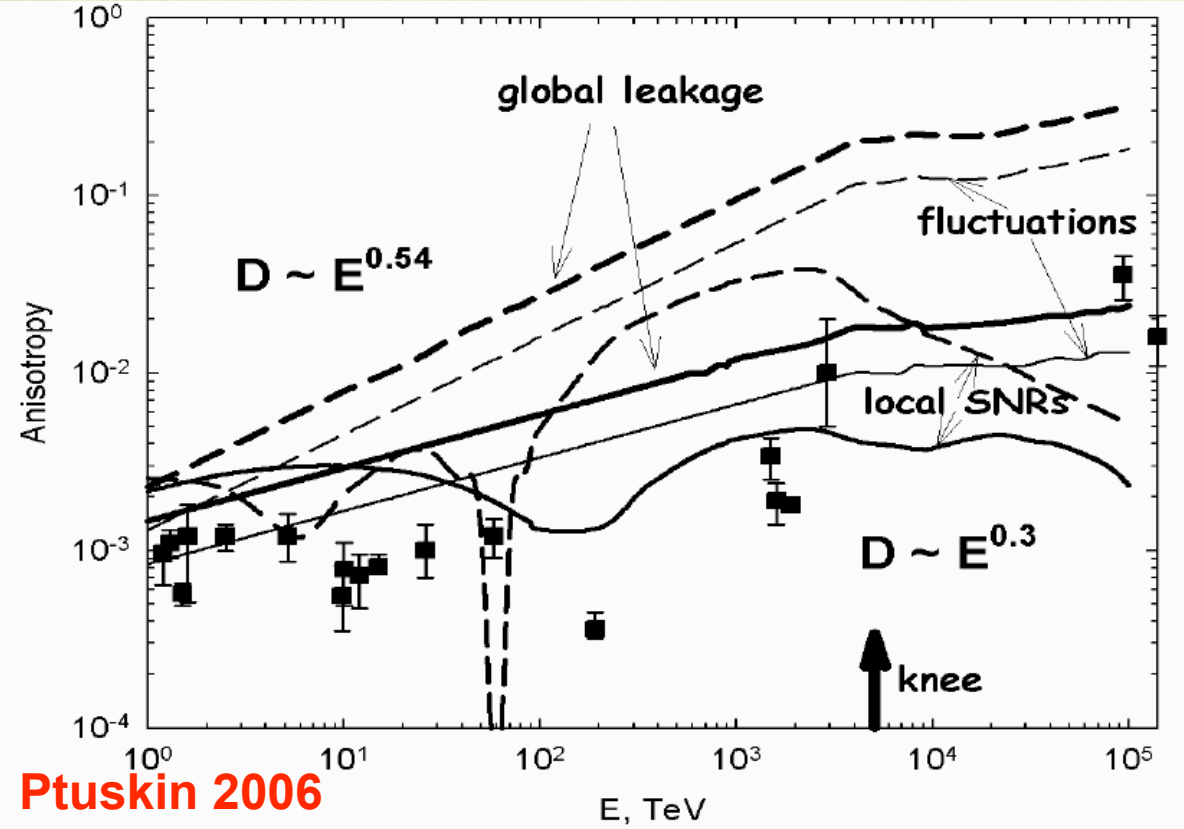


See Talk by Eun-Suk Seo

Secondary/Primary Ratios



Anisotropy



Ptuskin 2006

One should see an anisotropy also in the diffusive regime...
and it should become of order unity when:

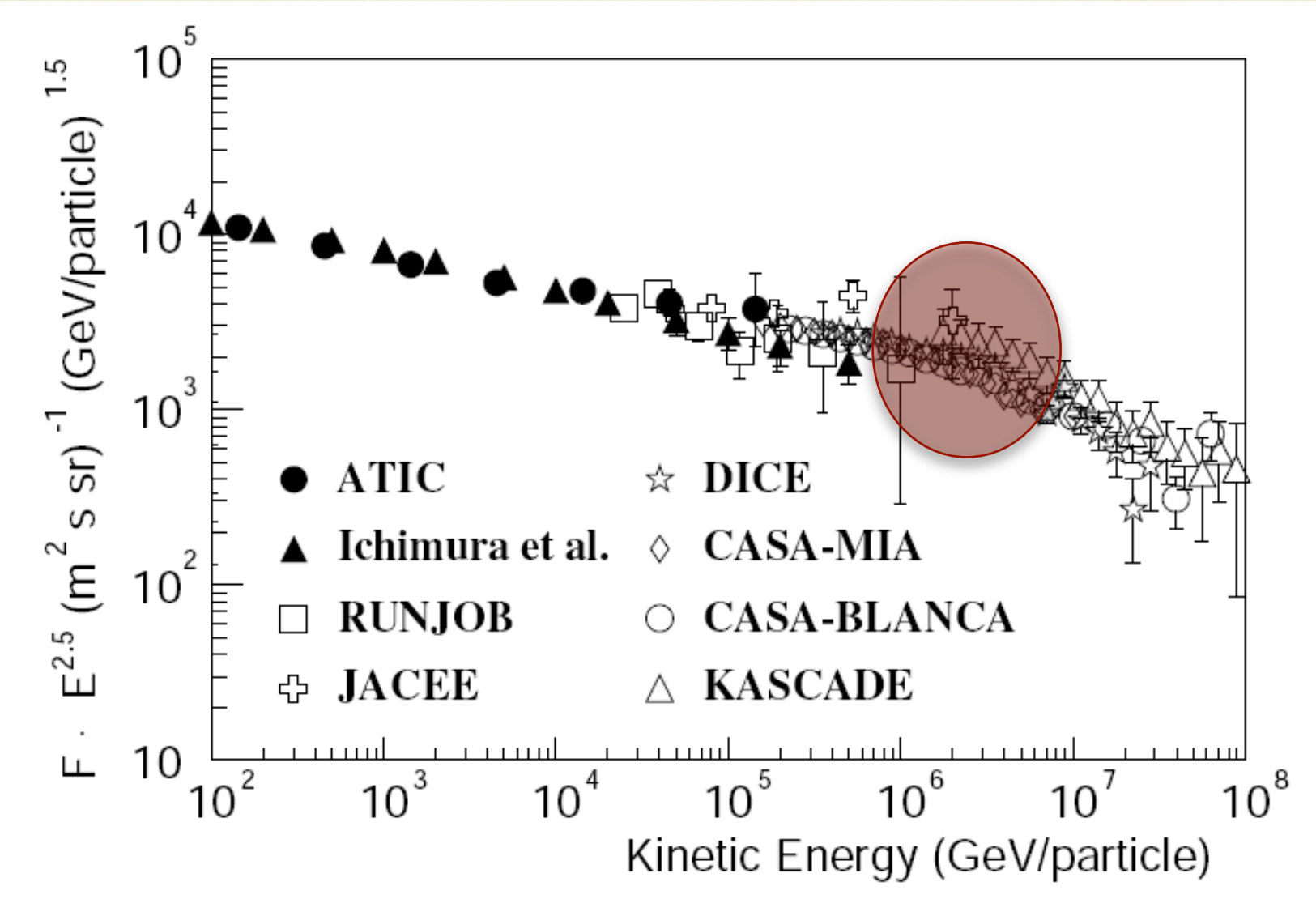
$$\frac{L^2}{4D(E)} < \frac{L}{3c}$$

Anisotropy should be steadily increasing with energy

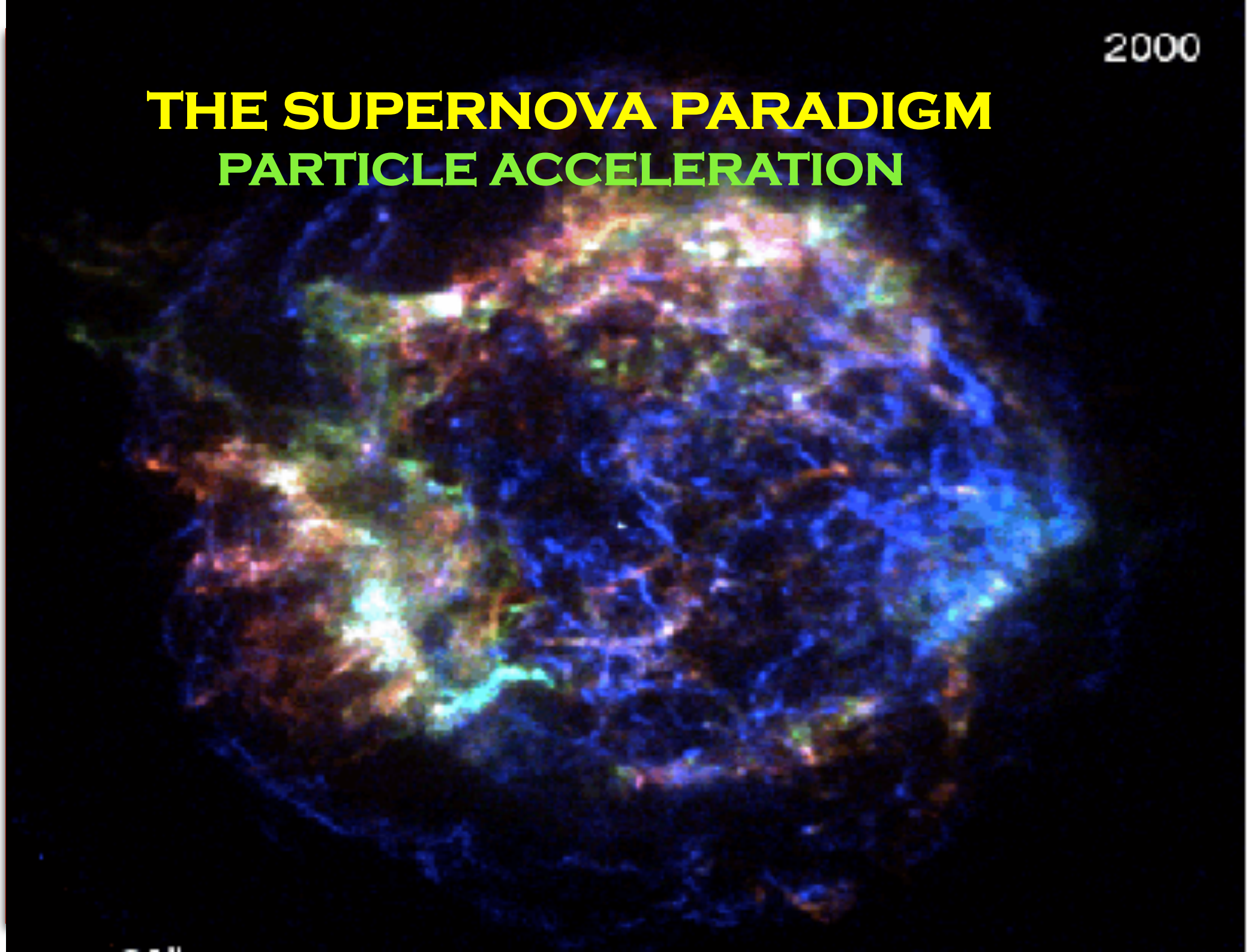
And reach unity around the knee (for slope of D(E) 0.6)

BUT both conclusions are known to be affected by stochasticity

All-Particle Spectrum



THE SUPERNOVA PARADIGM
PARTICLE ACCELERATION



TEST PARTICLE THEORY OF DIFFUSIVE SHOCK ACCELERATION

Krymskii 77, Blandford & Ostriker 1978, ...

1. POWER LAW SPECTRUM WITH SLOPE $\gamma = \frac{R+2}{R-1} \rightarrow 4$

2. LOW ACCELERATION EFFICIENCY REQUIRED

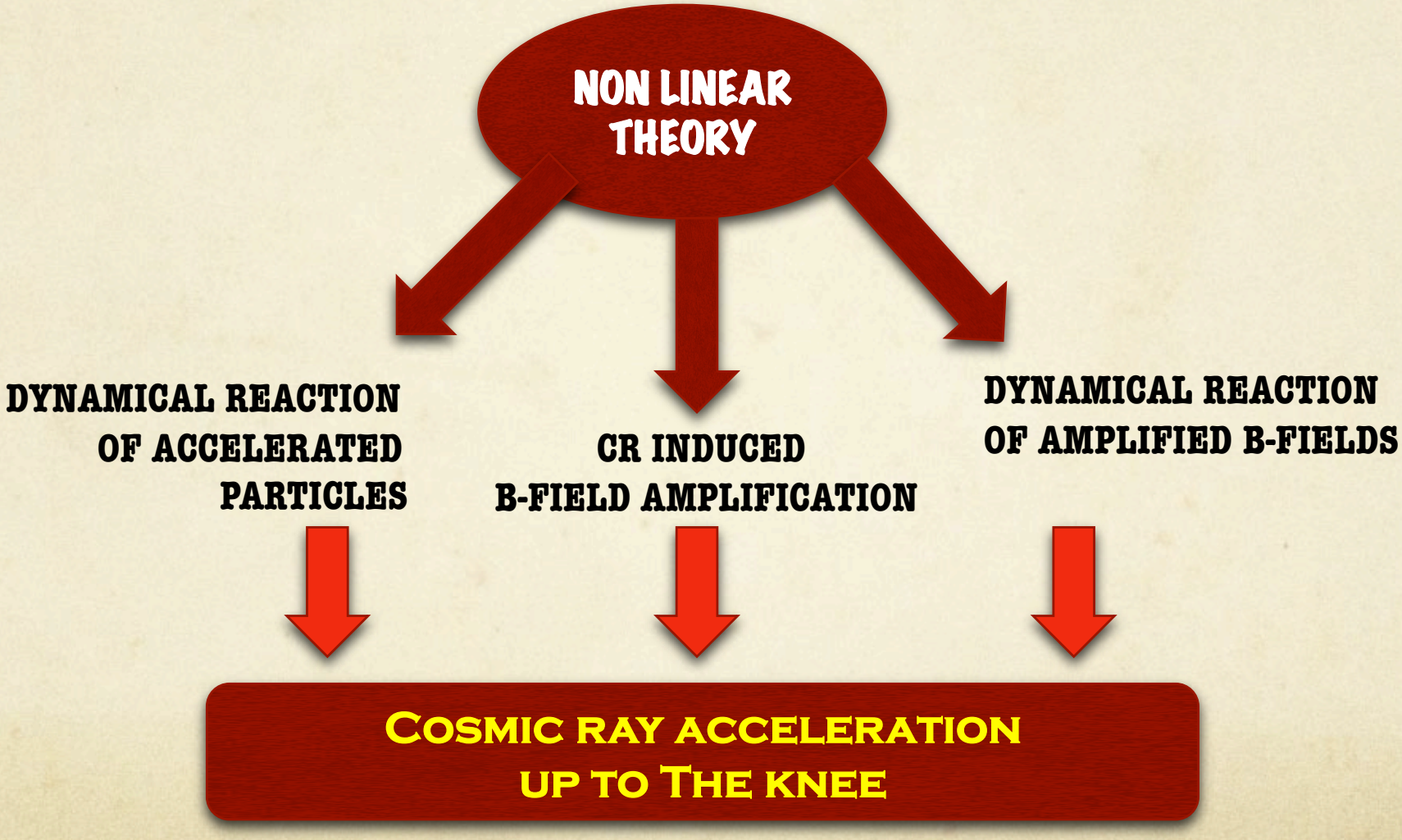
3. MAXIMUM ENERGY

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

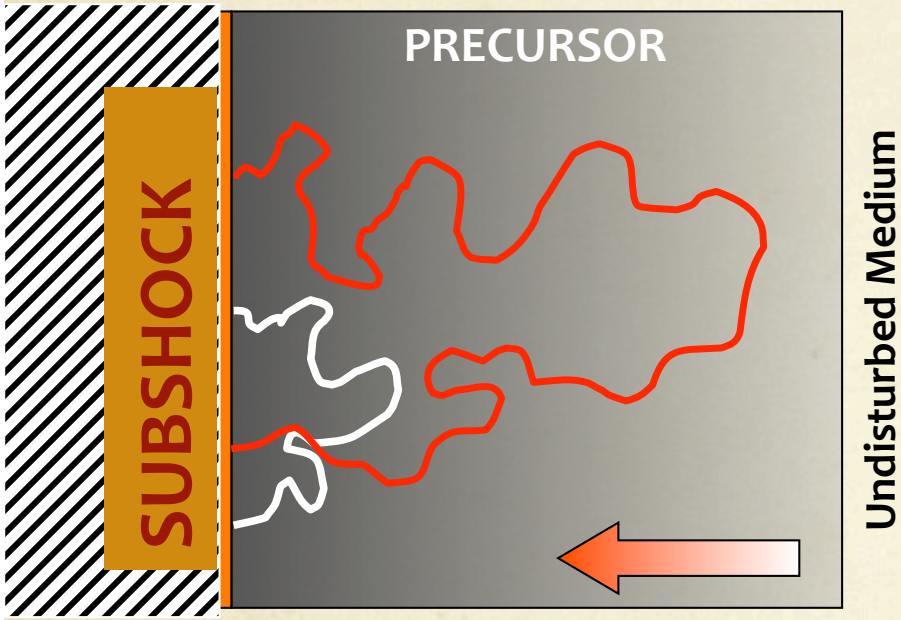
$\tau_{acc} \approx \tau_{age}$ → E_{max} ~ 1-100 GeV<<Knee

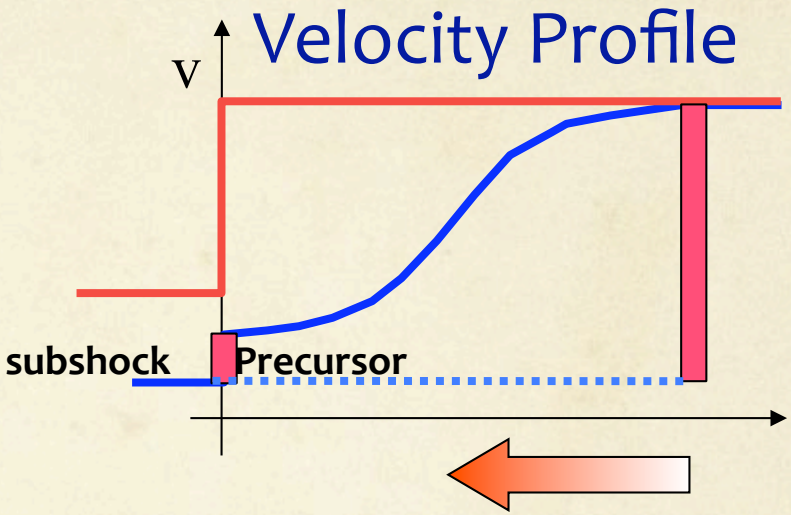
BEYOND TEST PARTICLES: *Non linear DSA*

Malkov, Berezhko & Voelk, Ellison et al, PB, Amato & PB...



DYNAMICAL REACTION



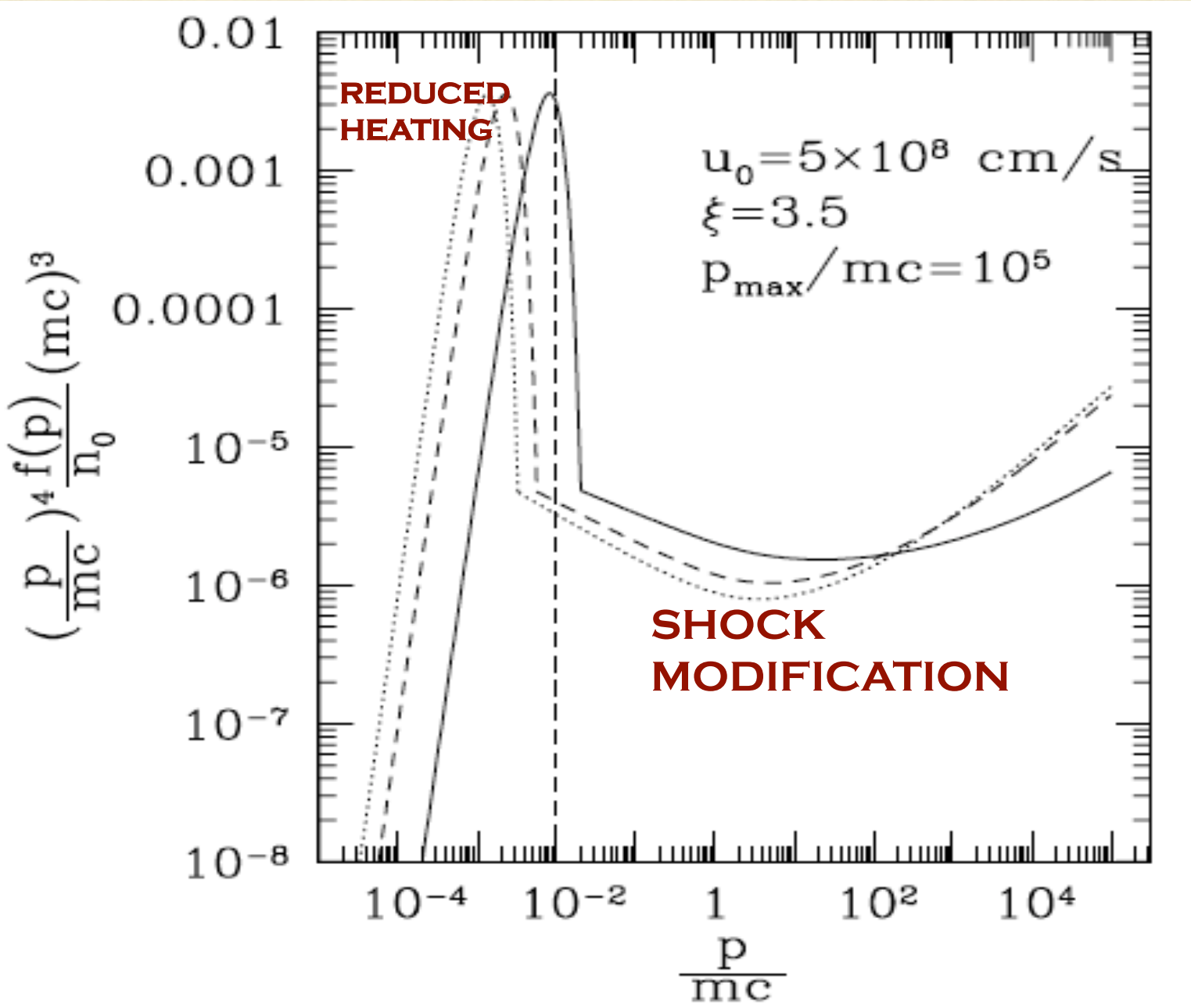


CR TRANSPORT EQUATION

+

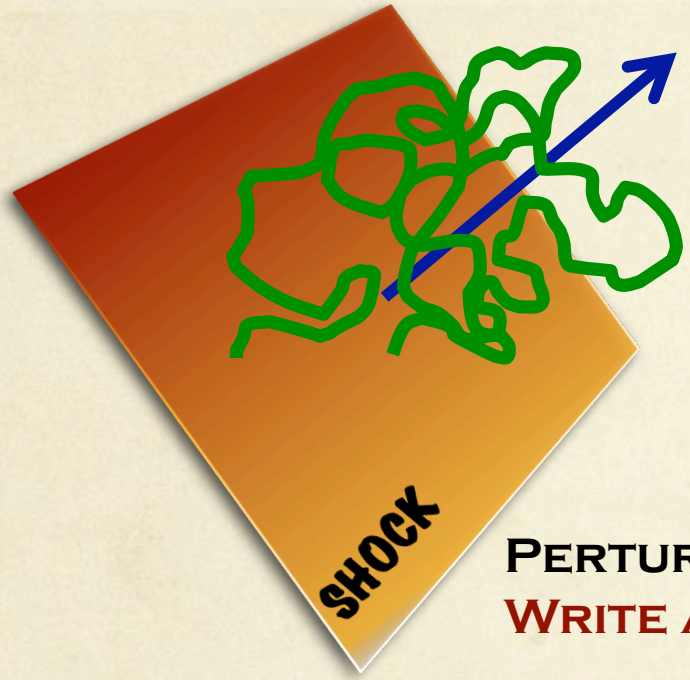
MASS, MOMENTUM, ENERGY CONSERVATION EQUATIONS

1. CONCAVE 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

PERTURBATIVE METHOD:

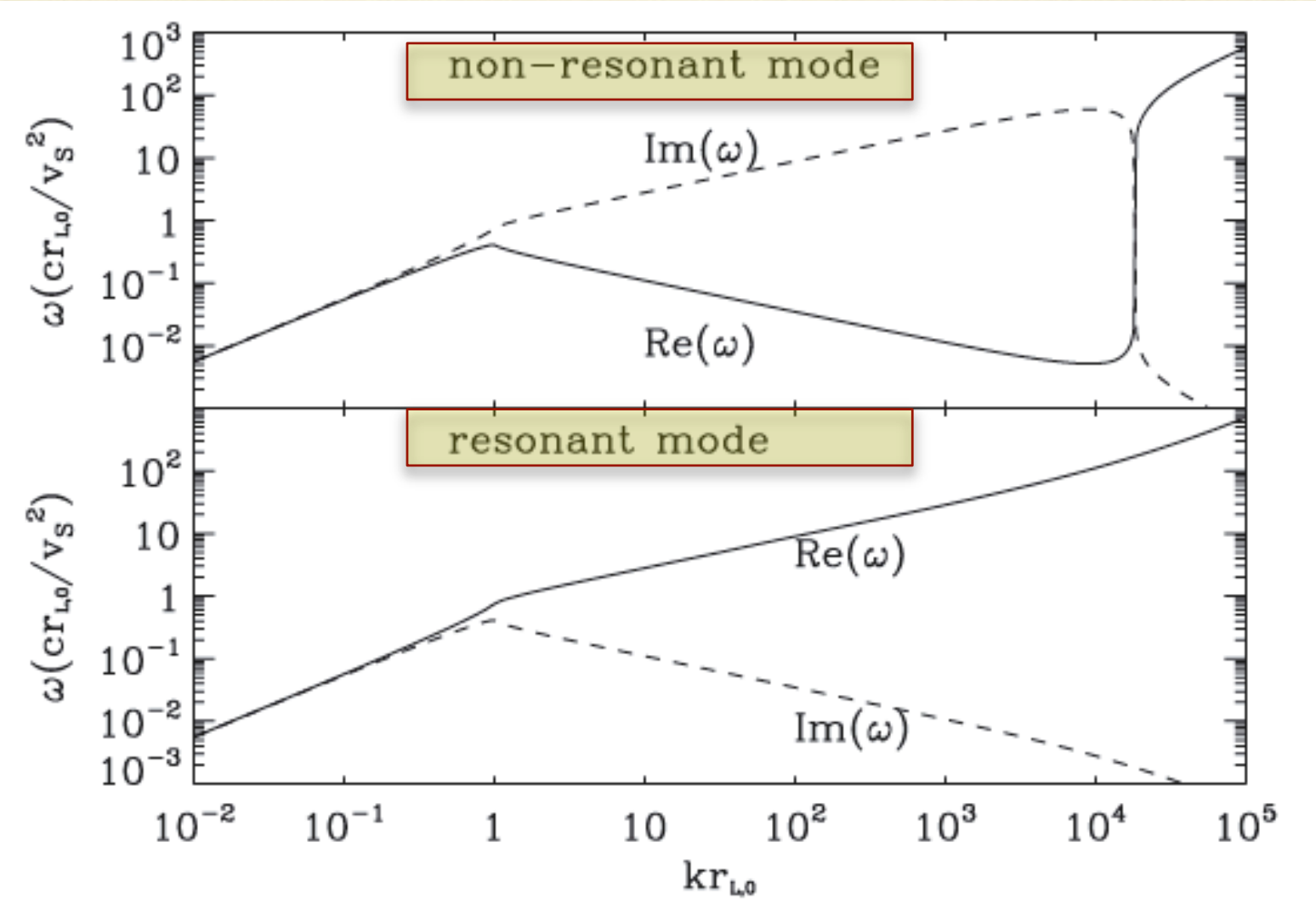
WRITE A VLASOV EQ FOR EACH PARTICLE TYPE

WRITE MAXWELL EQS FOR THE FIELDS

PERTURB THEM ALL

CHECK IF THERE ARE FOURIER MODES THAT DEVELOP A NEGATIVE IM(ω) UNSTABLE MODES

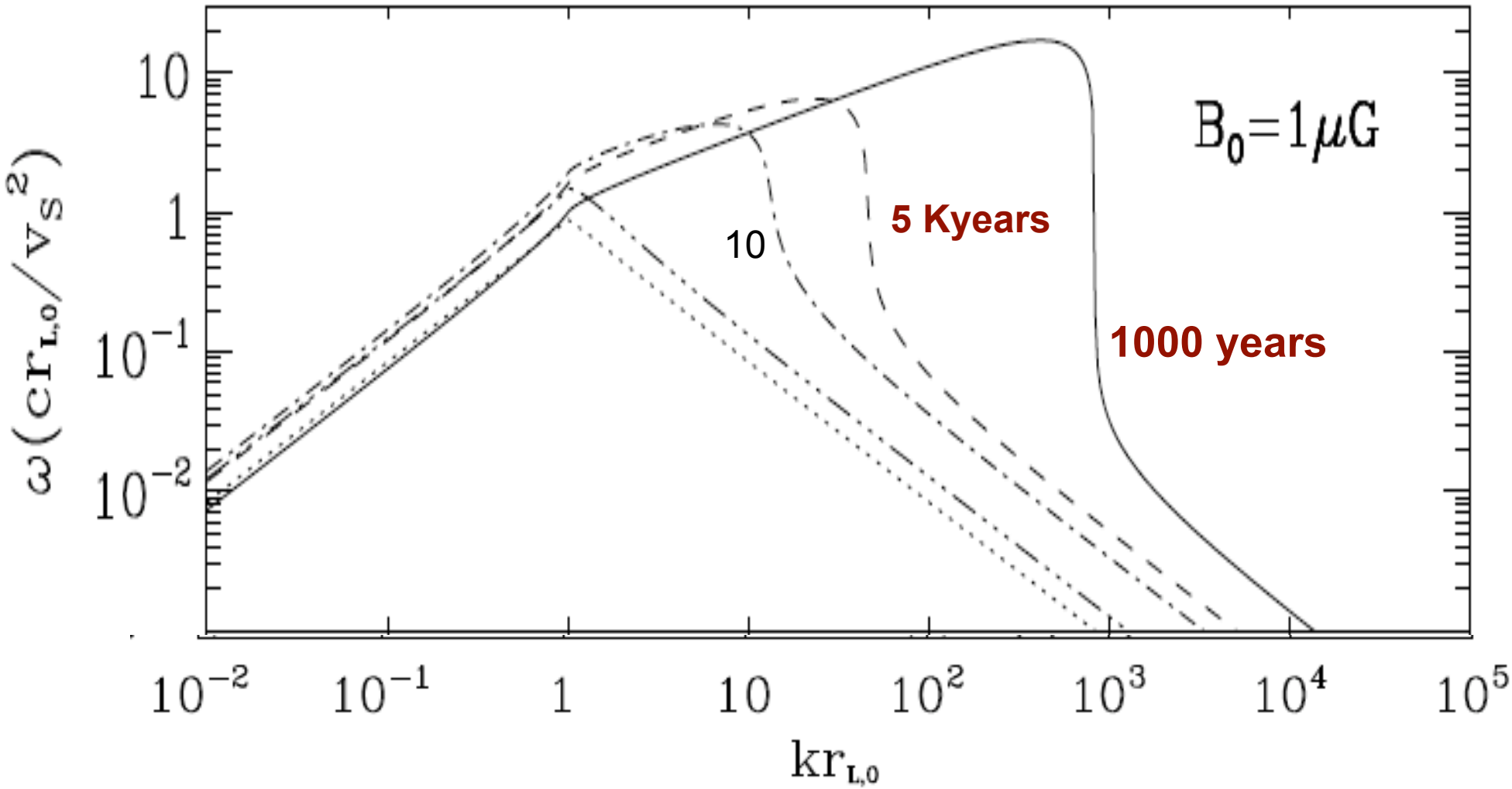
GROWING MODES



Amato & PB 2009, Bell 2004

NON-RESONANT MODES grow faster only in the early phases of a SN

Amato & PB 2009



SATURATION OF GROWTH

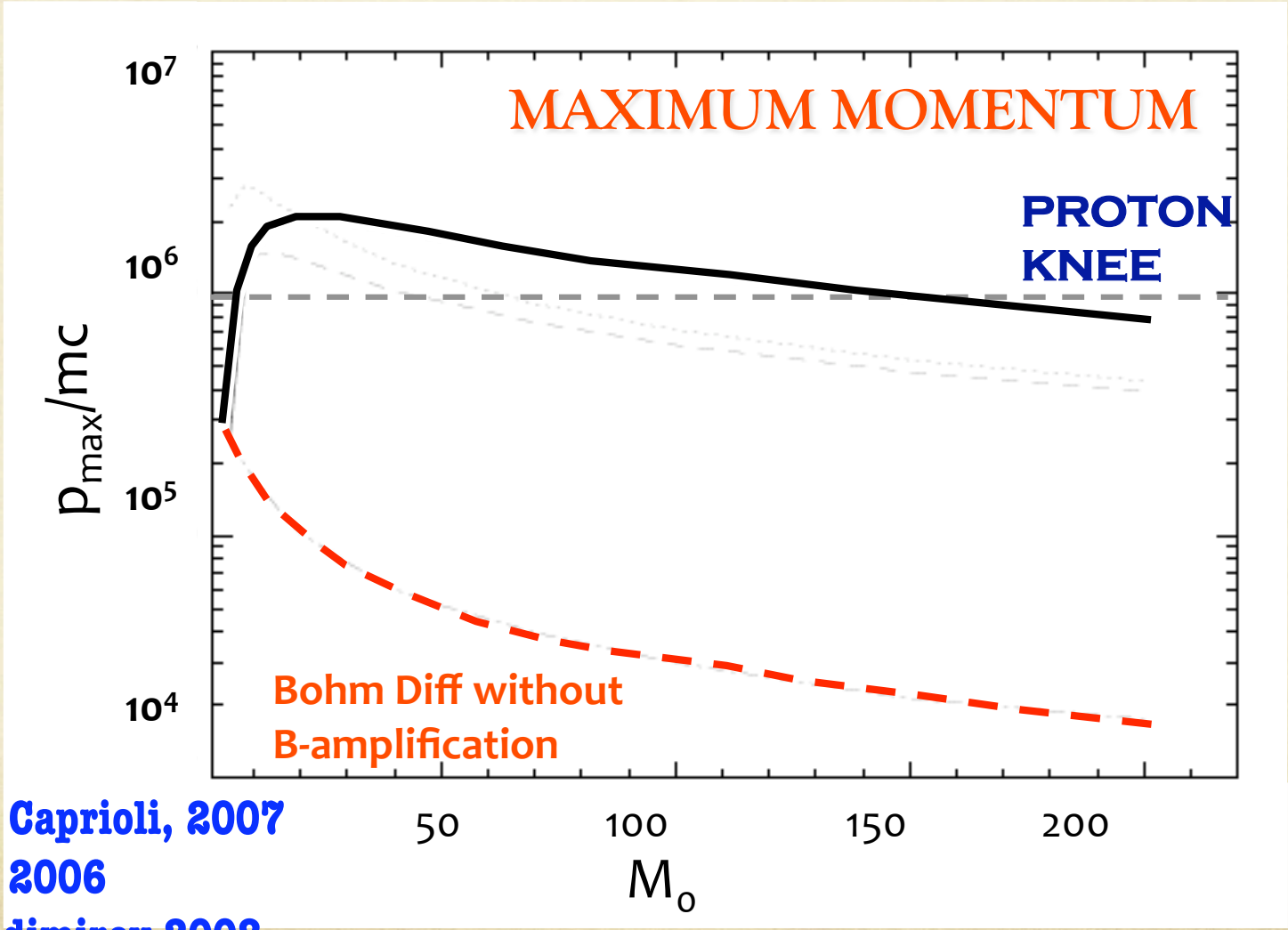
ALL RESULTS ARE OBTAINED IN PERTURBATIVE THEORY
BUT THEY LEAD TO NON-PERTURBATIVE CONCLUSIONS ($\delta B/B >> 1$).

HARD TO PREDICT THE REAL SATURATION LEVEL (Talk of Arons for PIC SIMULATIONS)

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
Ellison & Vladimirov 2008

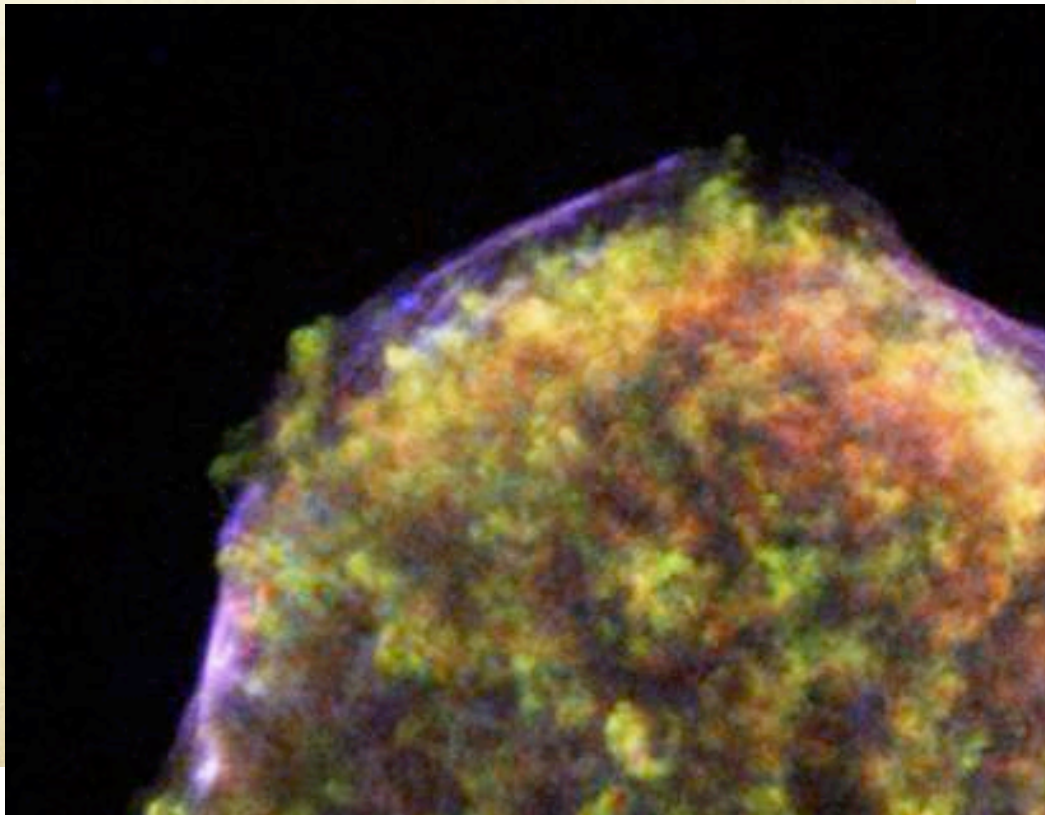
WHY IS IT INTERESTING:
II. Large B observed?

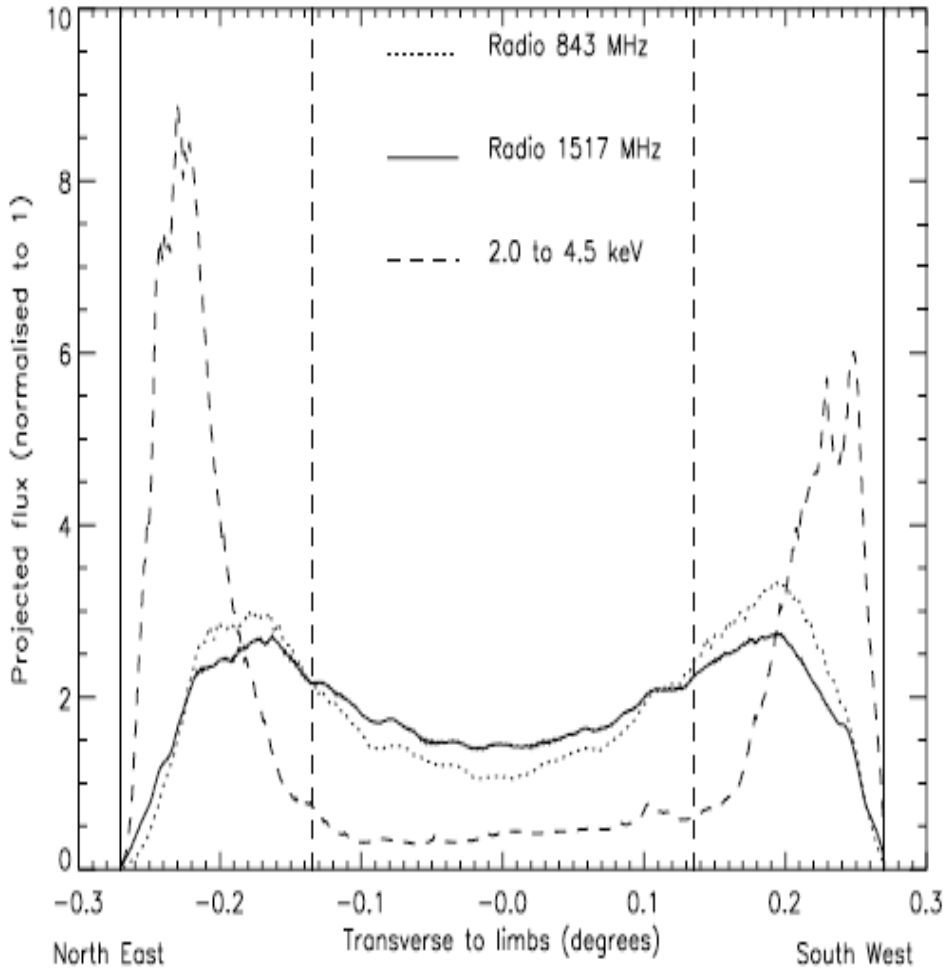
TYPICAL THICKNESS OF FILAMENTS: 10^{-2} -10^{-3} pc

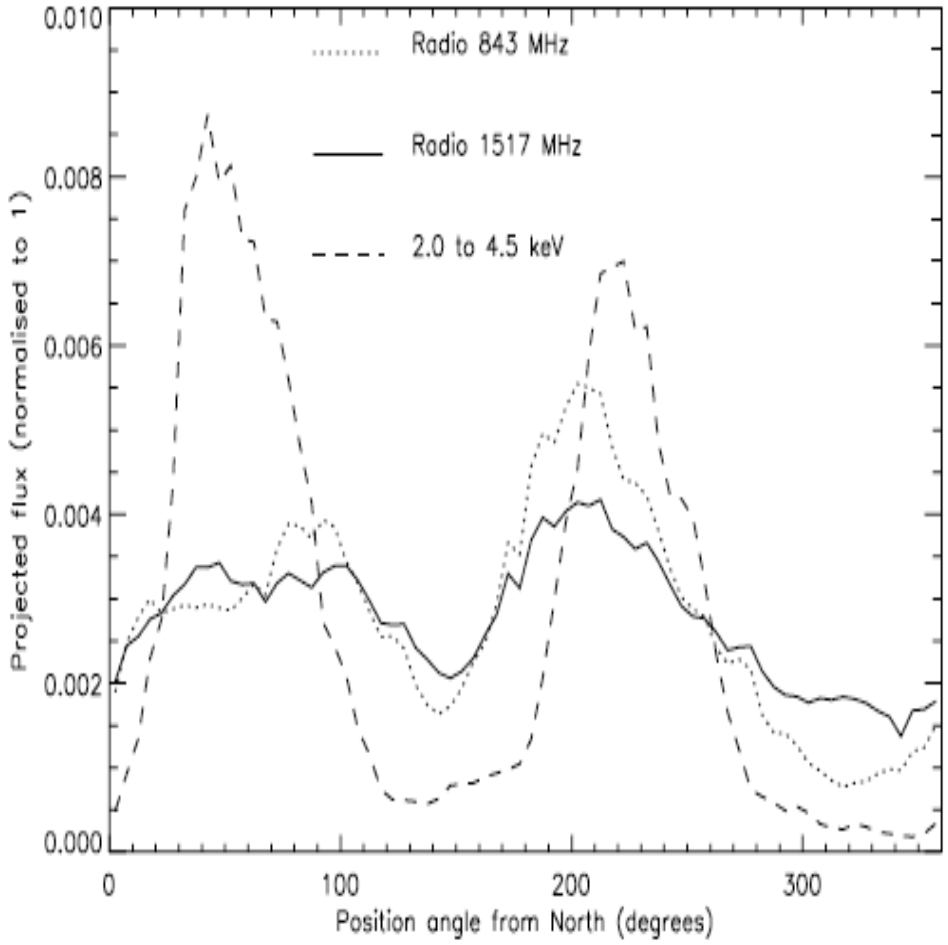
The synchrotron limited thickness is:

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

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







Rothenflug et al. 2004 **Geometry of the non-thermal emission in SN 1006**

WHAT DO STRONG B DO ?

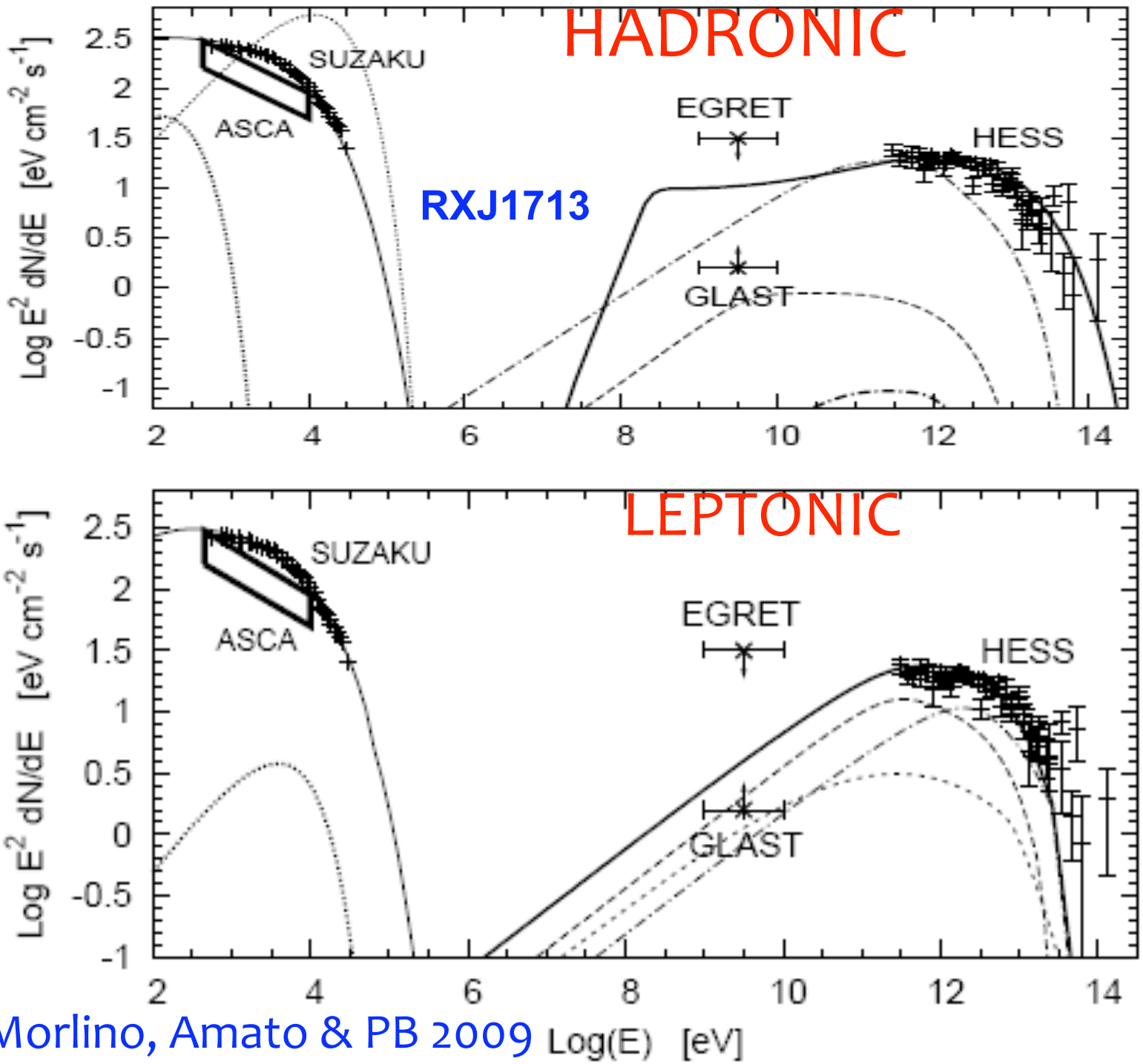
EVEN VERY LARGE B FIELDS HAVE NEGLIGIBLE PRESSURE COMPARED WITH THE RAM PRESSURE, BUT WHEN

$$\frac{B^2}{8\pi} > nkT \Rightarrow B > 6\mu G\ \mathrm{n}^{1/2}\left(\frac{\mathrm{T}}{10^4 K}\right)$$

T_0(K)	Λ_B	ξ_1	$p_{max}(10^6 GeV)$	R_{sub}	R_{tot}	S_{sub}	S_{tot}	$B_2(\mu G)$	$T_2(10^6$ K)
10^4	No	0.97	0.22	3.38	125.1	3.43	128.6	679.4	0.67
10^4	Yes	0.64	1.19	3.75	10.6	3.76	10.7	525.0	87.7
10^6	No	0.80	0.53	3.67	18.6	3.69	18.7	236.7	33.1
10^6	Yes	0.60	1.17	3.76	9.52	3.77	9.57	475.6	114.6

D

Caprioli, PB, Amato & Vietri 2008, 2009



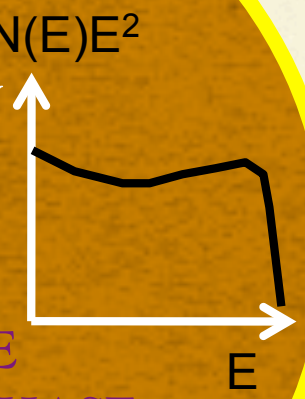
Morlino, Amato & PB 2009

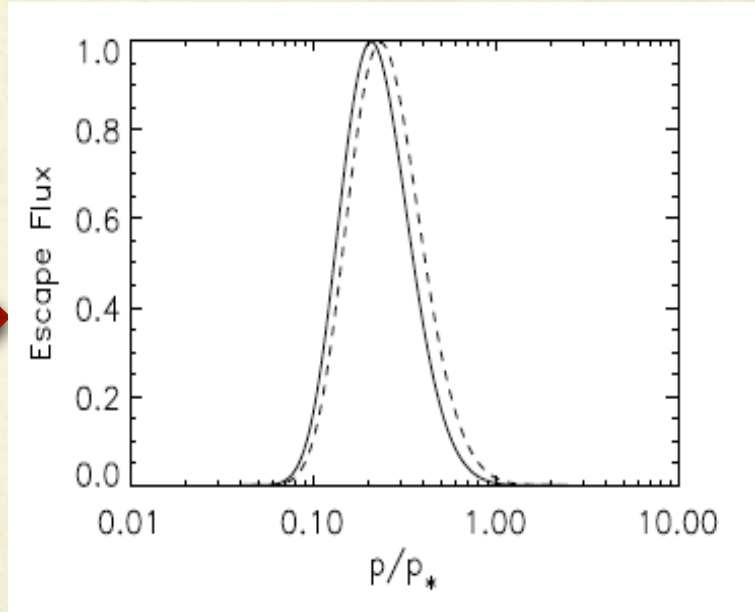
THE MISSING LINK BETWEEN CRs AND ACCELERATED PARTICLES

WHAT IS THE SPECTRUM OF CR AT EARTH?

Caprioli, PB & Amato 2009
Zirakashvili & Ptuskin 2005

EXPANDING SHELL + ADIABATIC LOSSES DURING THE SEDOV-TAYLOR PHASE





IN THE ABSENCE OF THIS ESCAPE FLUX ADIABATIC LOSSES WOULD MAKE REACHING THE KNEE IMPOSSIBLE

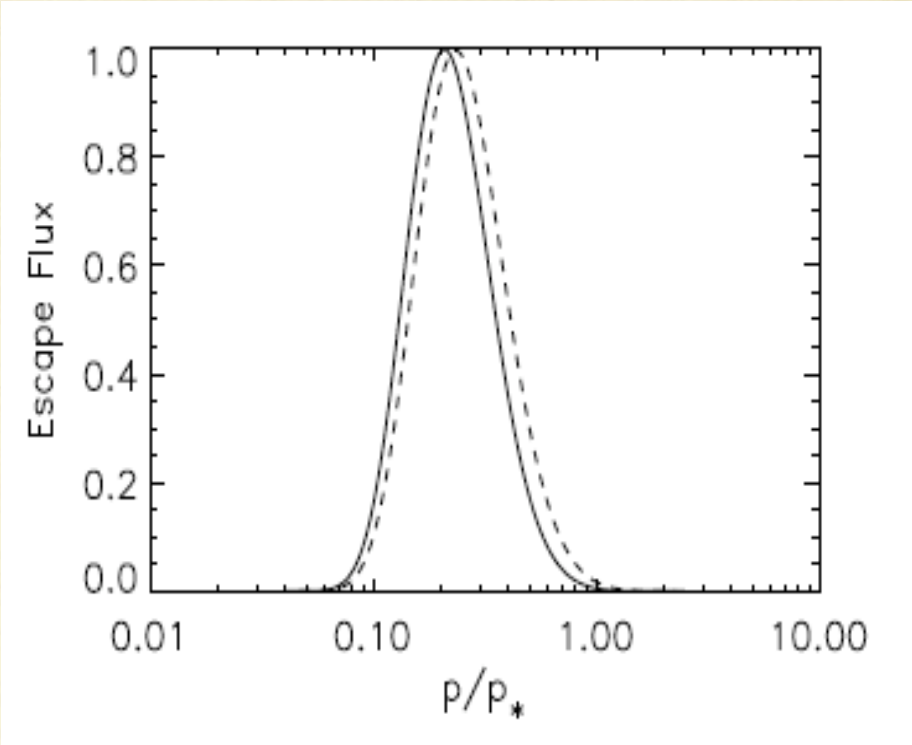
ESCAPE FLUX WITH TIME

Caprioli, PB & Amato 2009
Zirakashvili & Ptuskin 2005

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

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

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



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

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

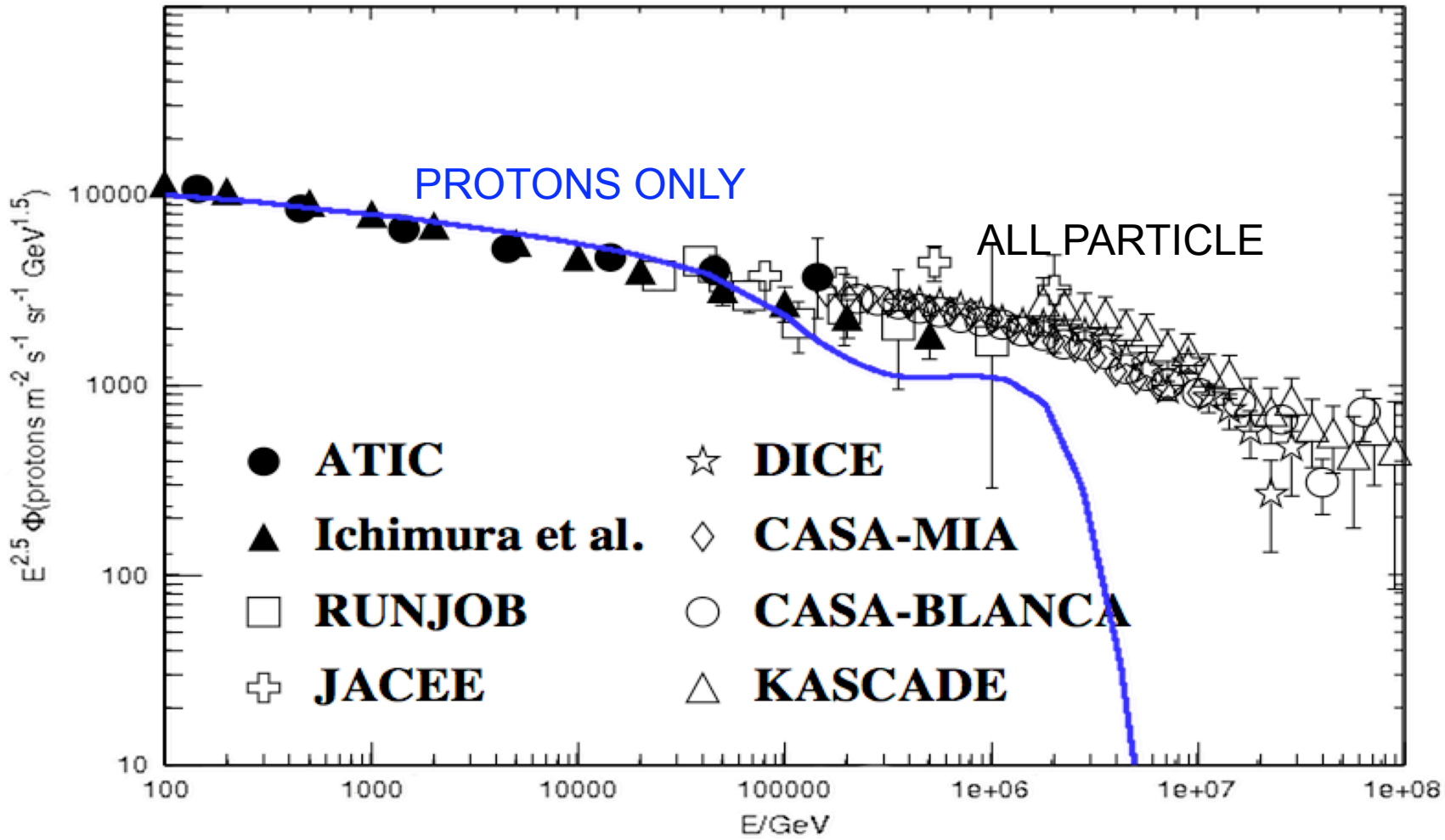
So...

The spectrum of CR observed at the Earth is NOT the Same as in the sources!

What we see on Earth is the the result of convolution of the Escape time over the sedov-taylor phase of the SNR Evolution, including the crucial effect of ADIABATIC Energy losses

In the absence of this escape flux SNR would be unable To account for acceleration to the knee

PREDICTED SPECTRUM



Caprioli, PB & Amato 2009

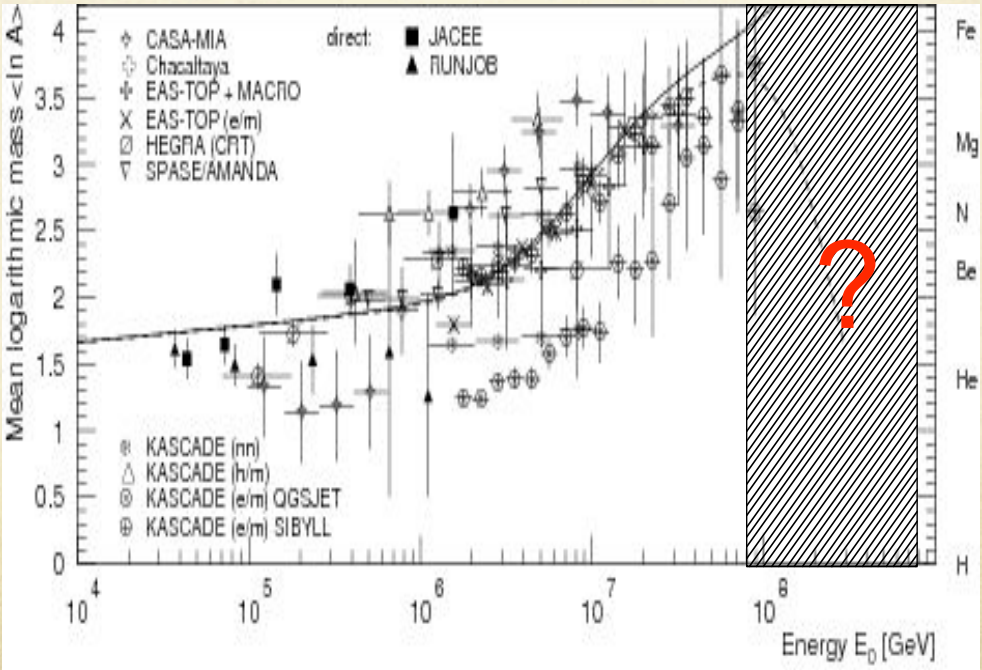
SOME IMPLICATIONS

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



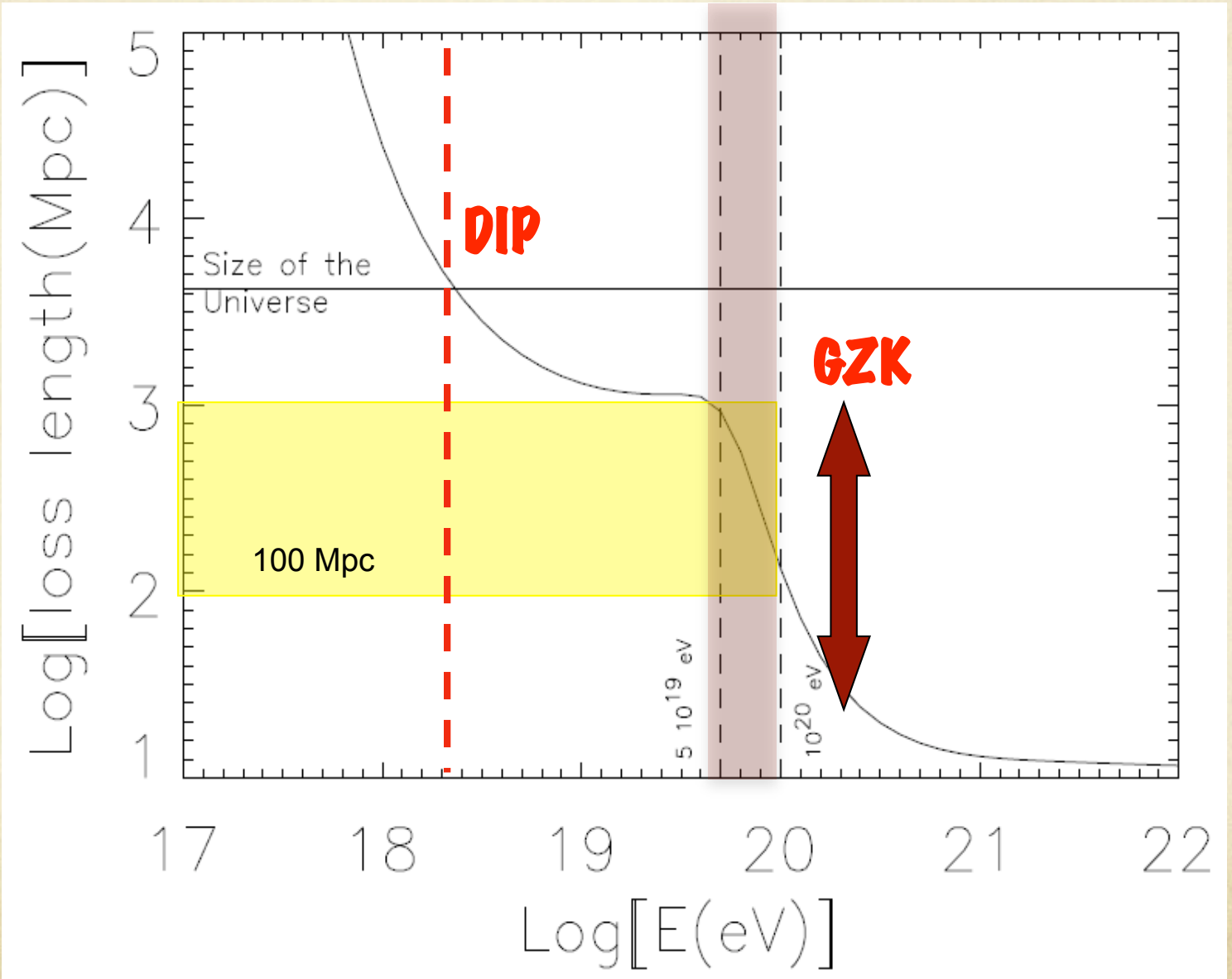
THE TRANSITION

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

2. Observations also suggest (not prove) the same trend

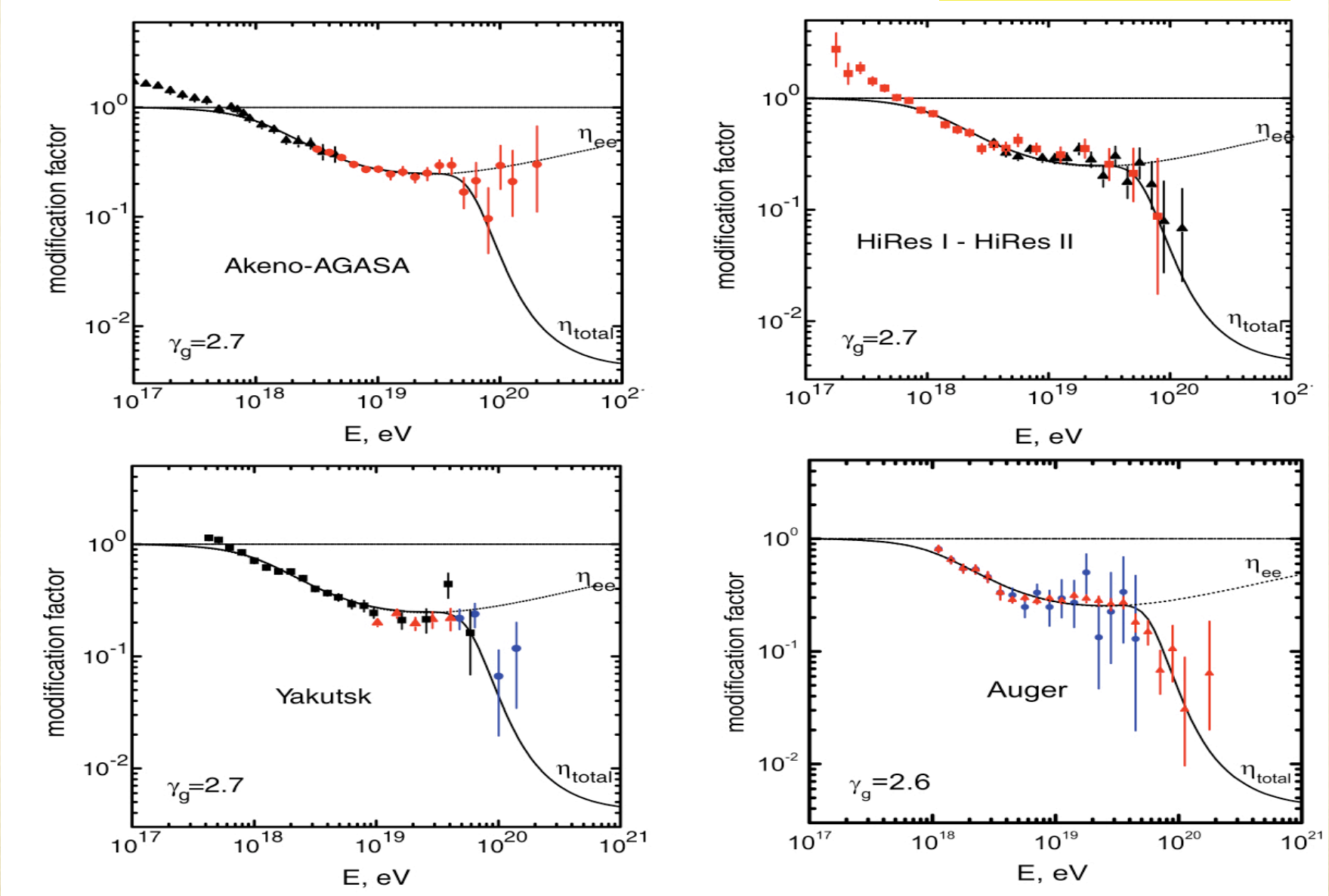
DIP MIXED ANKLE

PROPAGATION OF PROTONS



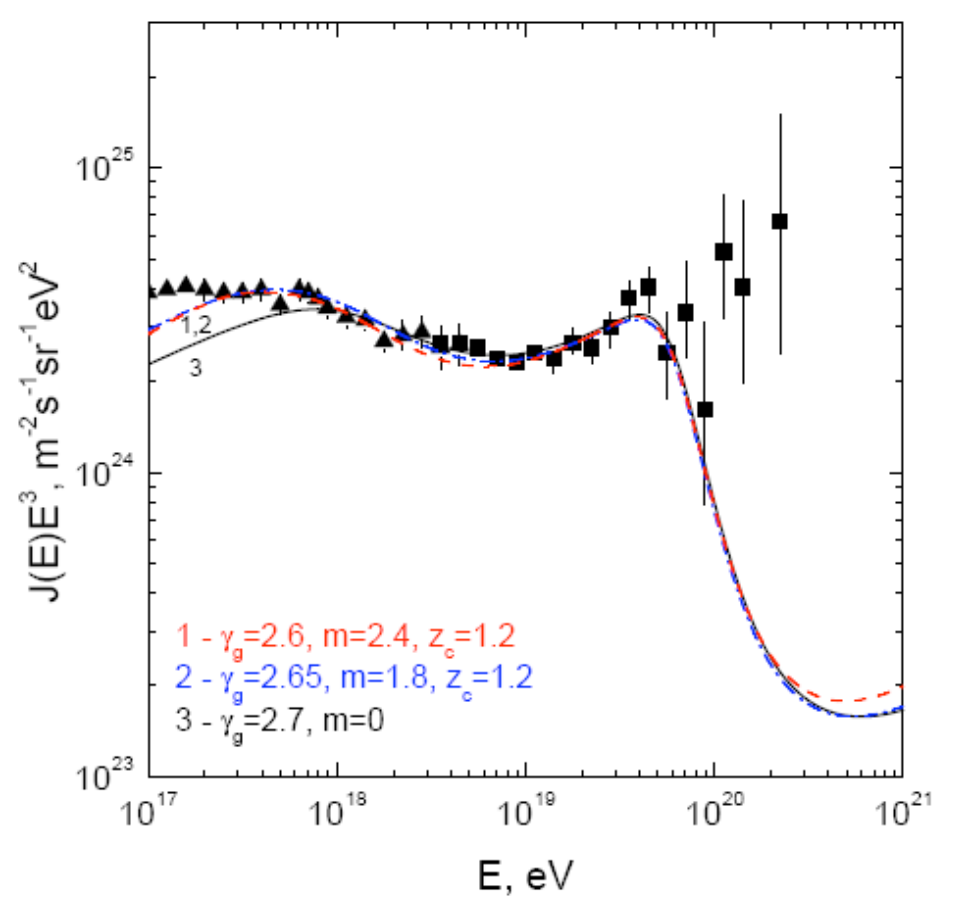
MODIFICATION FACTOR

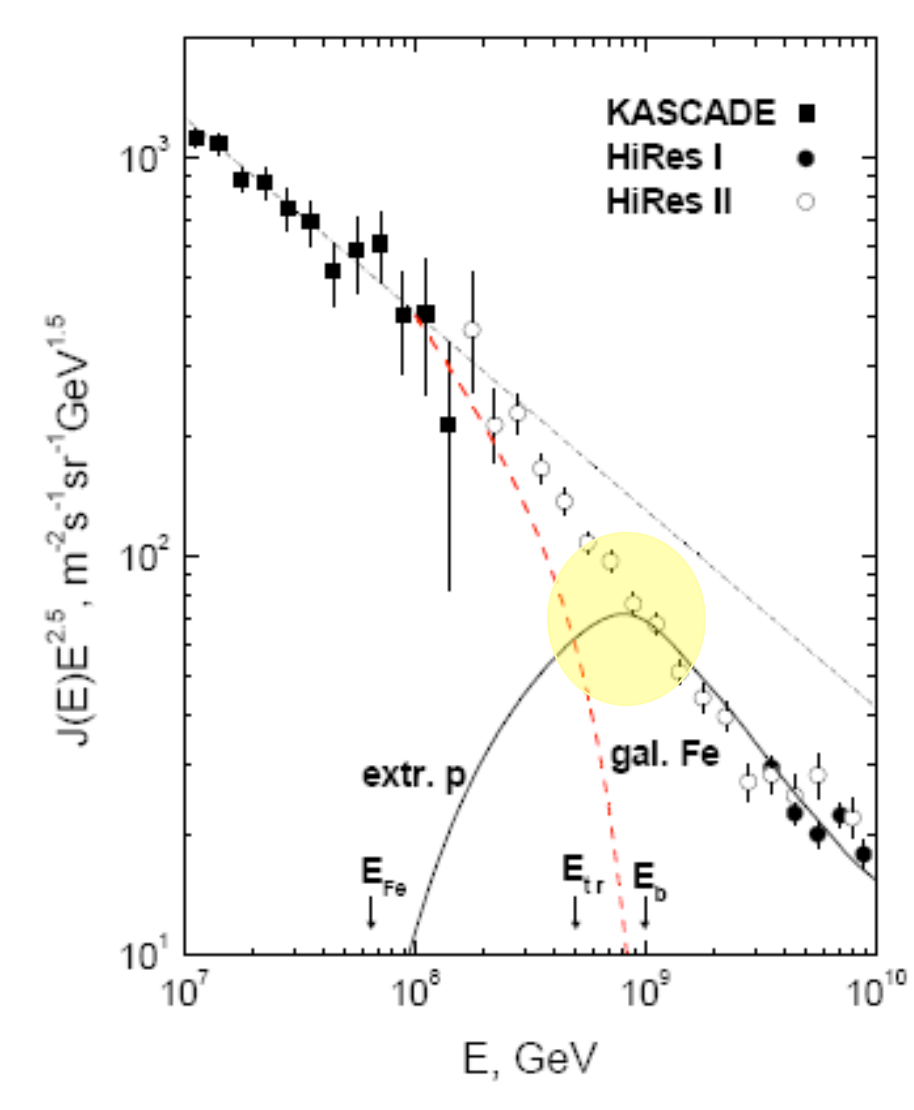
$$\eta = \left(\frac{J_p(E)}{J_p^{unm}(E)} \right)$$



Aloisio, Berezinsky, PB & Ostapchenko 2008

HOW DOES THE SPECTRUM LOOK LIKE? THE DIP

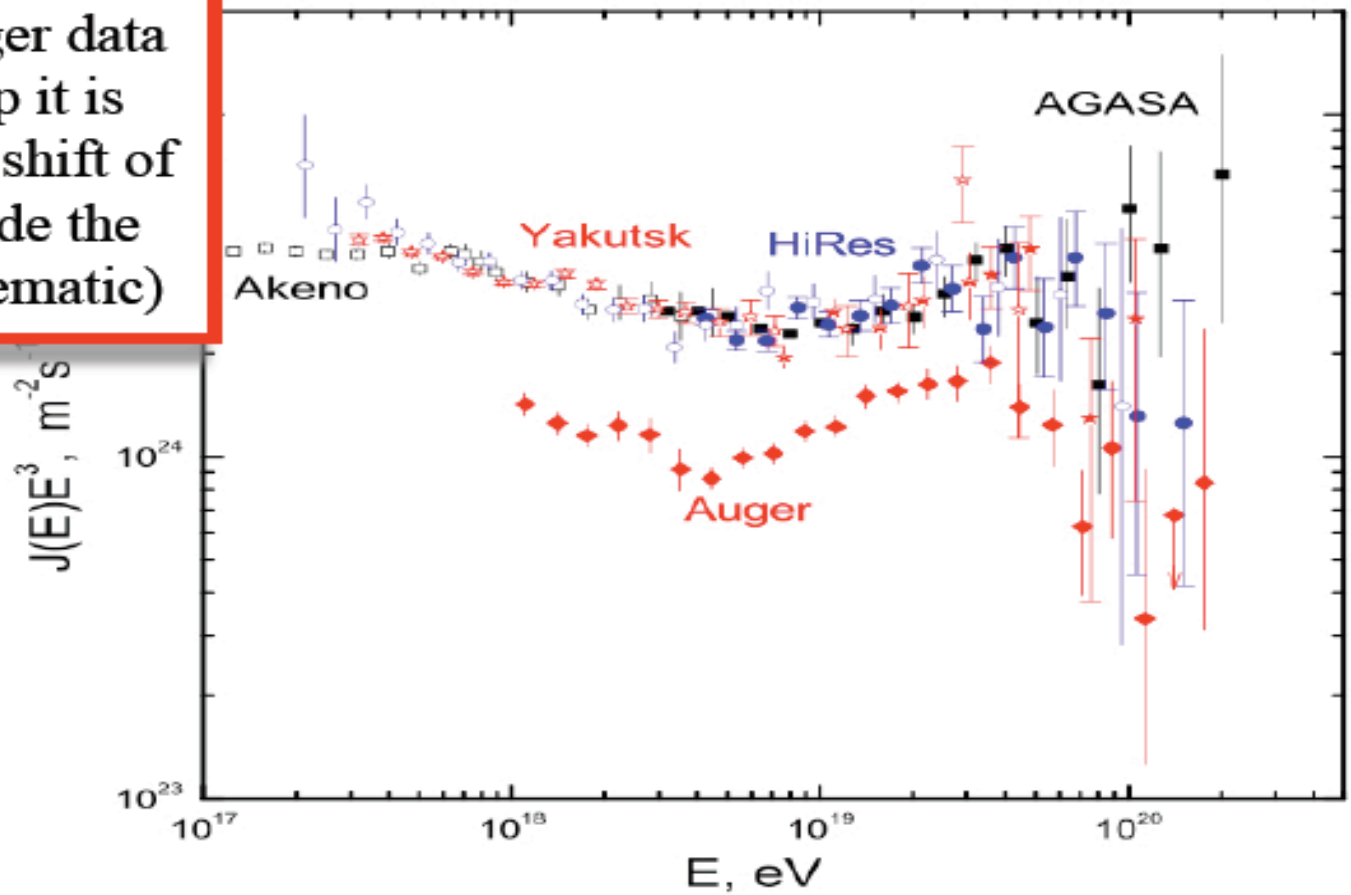




Berezinsky et al. 2005
Aloisio et al. 2007

ACCIDENT OR PHYSICS?

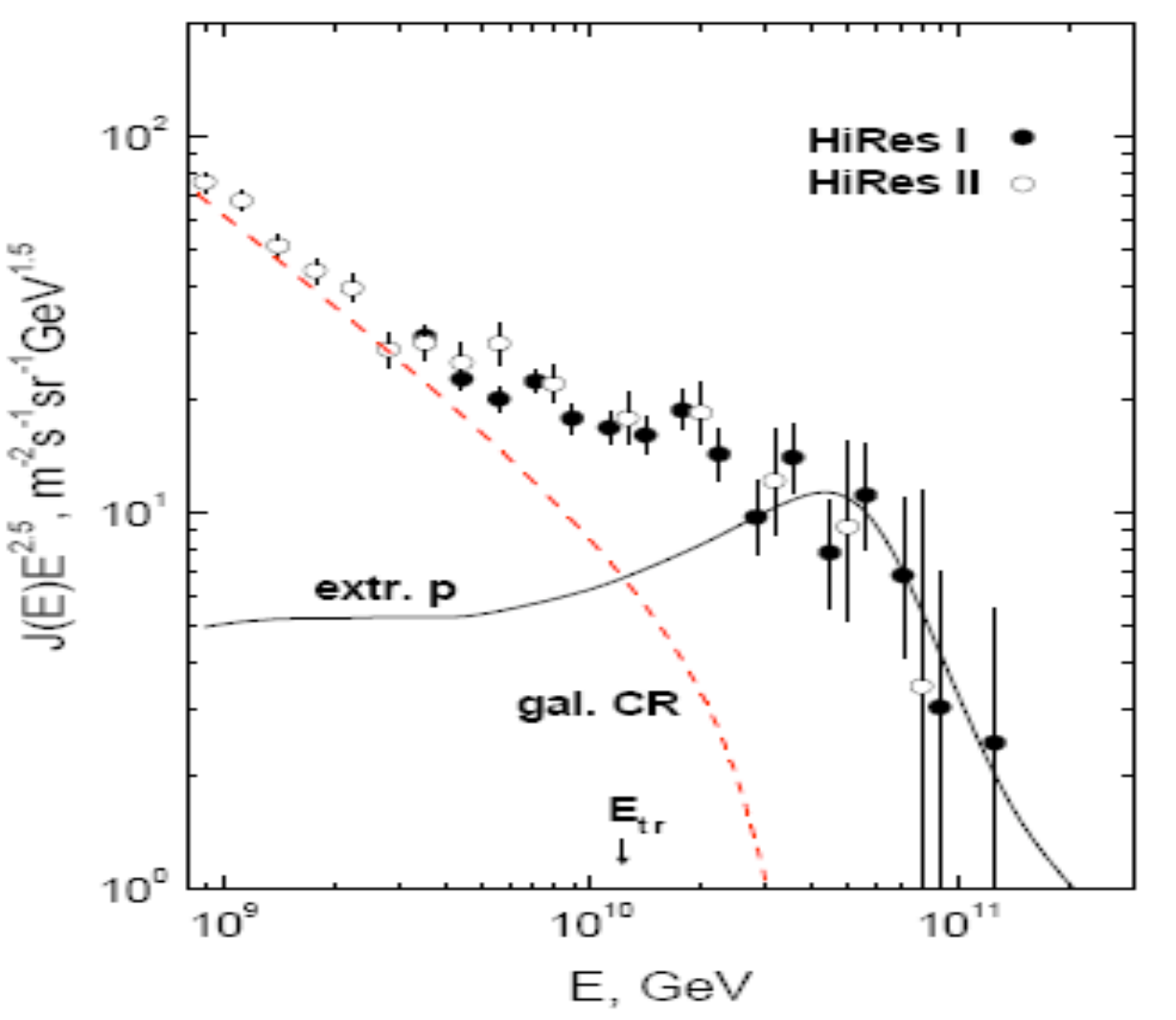
to calibrate the Auger data by the protons dip it is required an energy shift of about 50% (outside the experimental systematic)



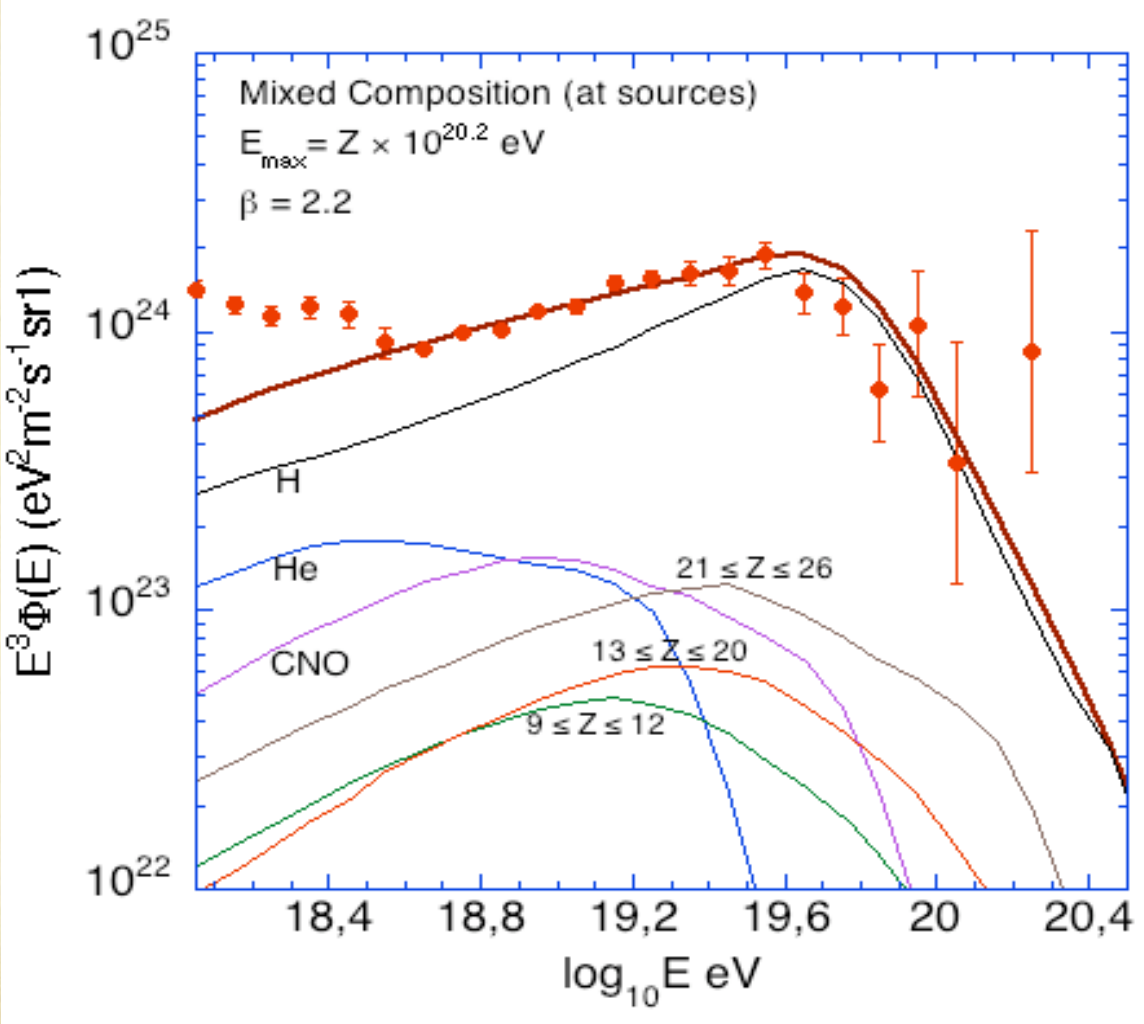
Berezinsky et al. 2006
Aloisio et al. 2007

ENERGY SHIFTS WITHIN SYSTEMATICS FOR ALL EXPS BUT Auger

HISTORICAL INTERPRETATION OF THE TRANSITION: THE ANKLE

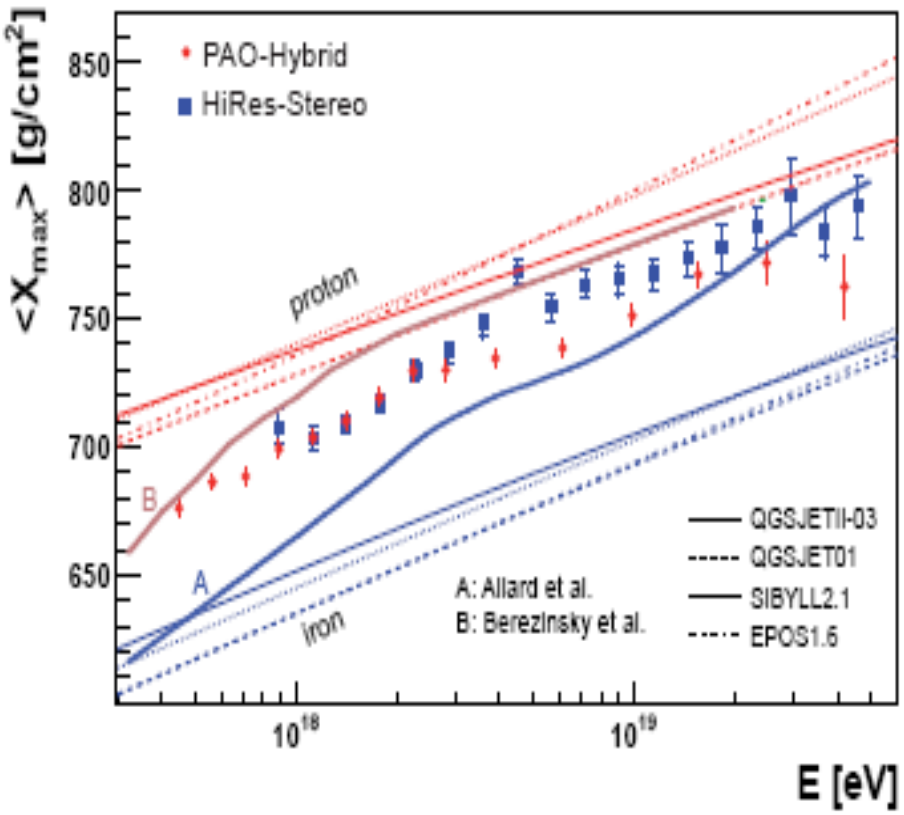


ALTERNATIVE INTERPRETATION OF THE TRANSITION: MIXED COMPOSITION



Allard et al. 2005-2008

UNDERSTANDING THE DIFFERENCE:
DIP VS MIXED



From Kampert 2008

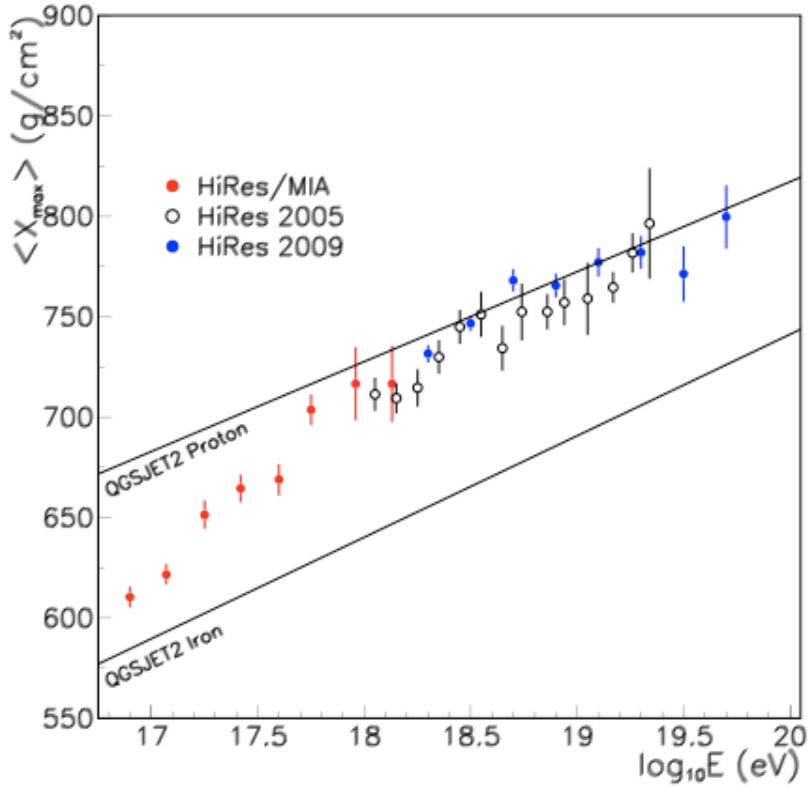
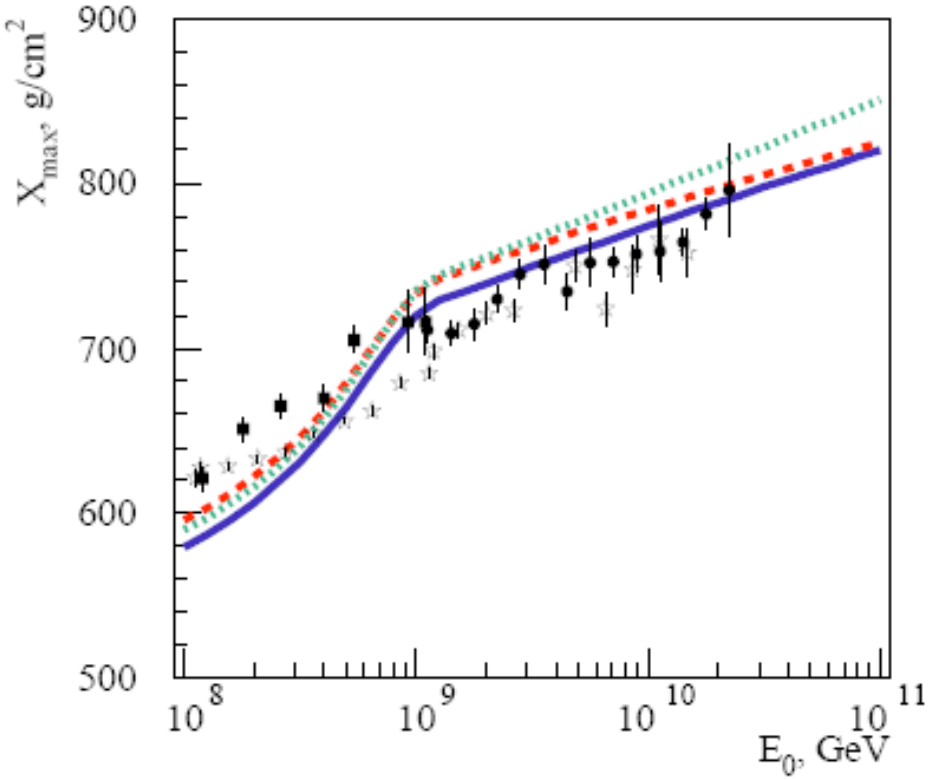


Fig. 25.— Comparison of current HiRes stereo $<X_{max}>$ results with results from the HiRes-prototype/MIA hybrid (Abu-Zayyad et al. 2001) and previously published HiRes stereo results (Abbasi et al. 2005).

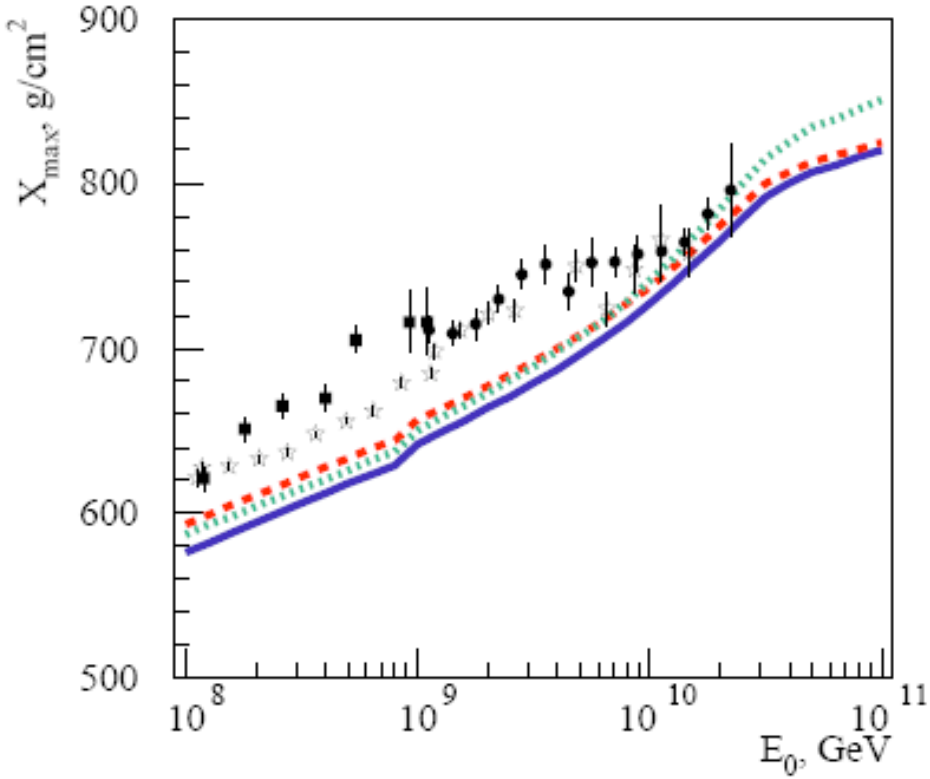
From Sokolsky, SoCoR Workshop

UNDERSTANDING THE DIFFERENCE:
DIP VS ANKLE

DIP



ANKLE



Aloisio, Berezinsky, PB & Ostapchenko 2008

CONCLUSIONS

Though not proved yet, the SNR paradigm for the origin of Galactic CR is in excellent shape

The most interesting recent discovery supporting it has come from X-ray observations: thin filaments → large B-fields

Protons can be accelerated up to the knee…and heavier nuclei to energies Z times larger

If the observed proton knee is due to the max energy, then Galactic CRs should end at the second knee

It is of the utmost importance to measure the chemical composition In the energy region 10^{17}-10^{19} eV in order to

1. understand the transition
2. understand what is going on for UHECR