Progress and Problems with Supernovae as Sources of Cosmic Rays

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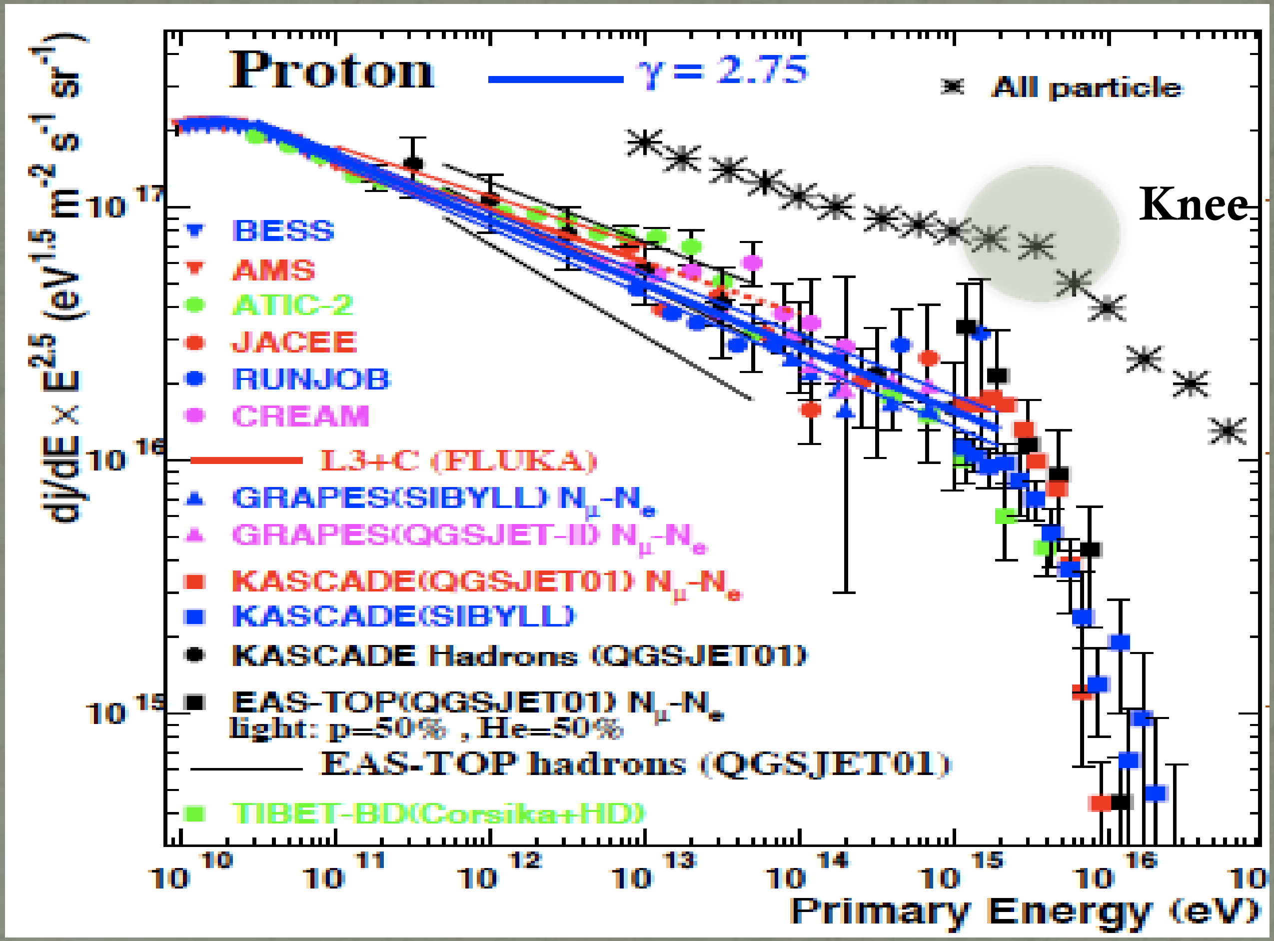
What are we trying to understand? The Absolute minimum...



From Bertaina et al. 2008

+ Chemical composition & Anisotropy (Later...)

General framework: Non Linear DSA and SNRs

Particle acceleration occurs mainly at the forward shock of supernovae explosions

Energy conversion → Non linear DSA

Thermodynamic quantities as outputs

Accelerated particles are then convected downstream → Adiabatic losses

Escape from upstream during the Sedov phase crucial for CR

Main signatures of the theory:

1. Efficient acceleration
2. Concave spectra of accelerated CR and secondary radiation
3. Decrease of heating in the downstream plasma
4. Magnetic field amplification
5. Gamma rays if enough target

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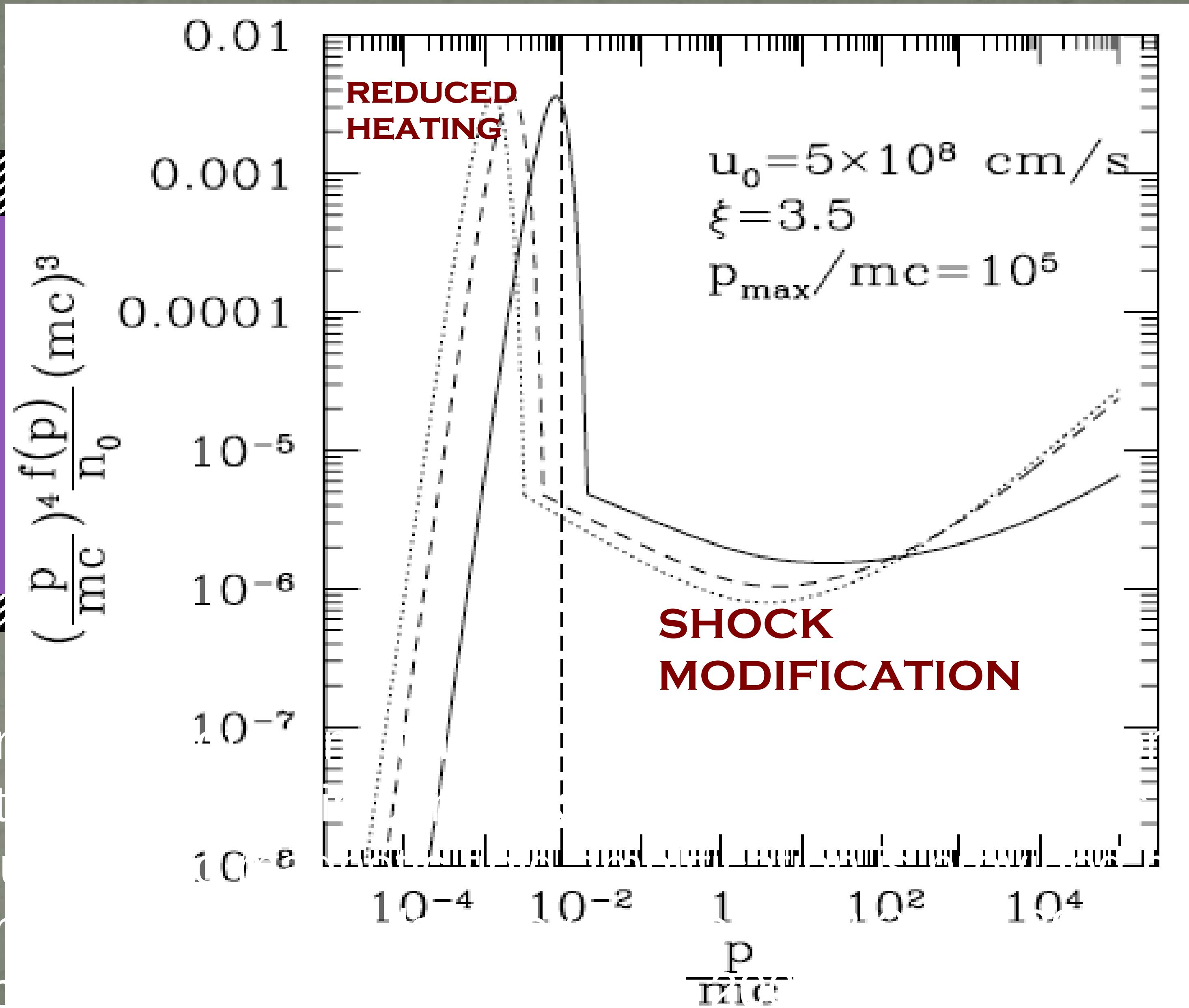

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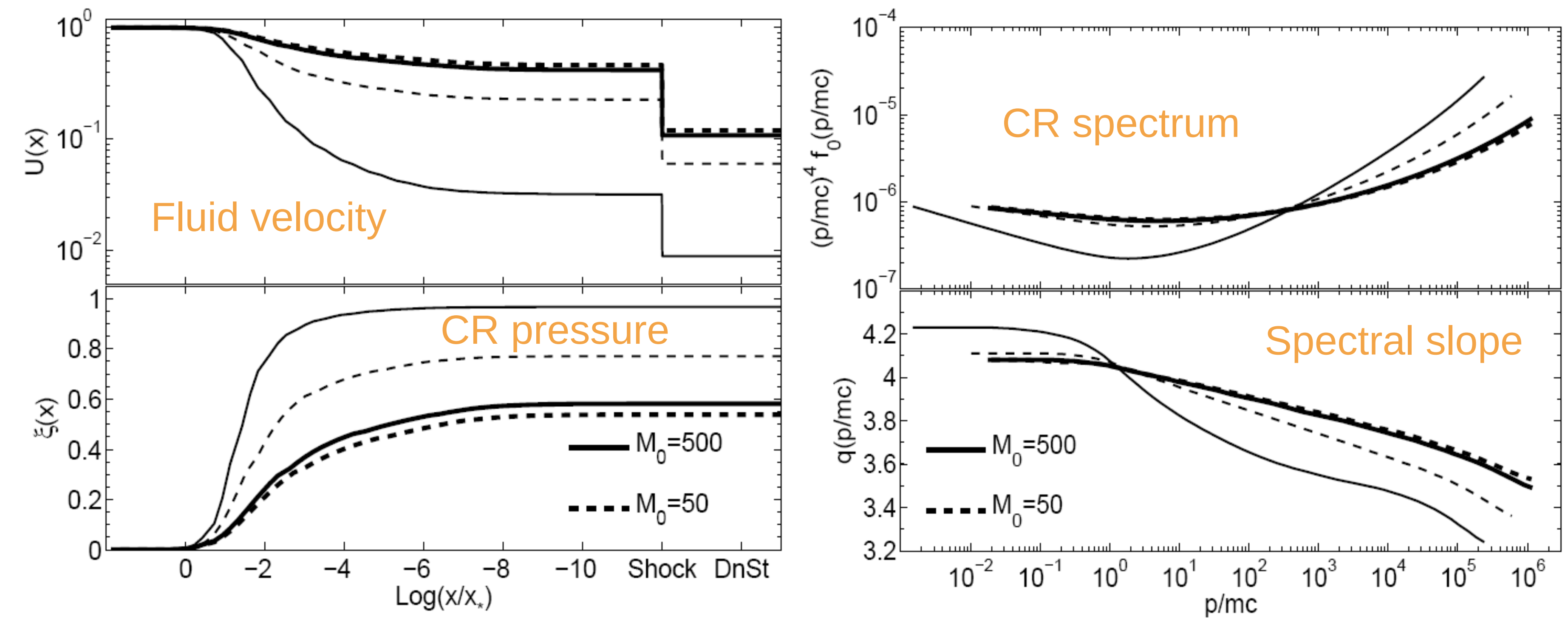
PB, Gabici & Vannoni 2005, Amato &PB 2005, 2006

TYPICAL RESULTS



Caprioli, PB, Amato & Vietri 2009

GOALS

Explain the multi-ν spectra of SNRs checking
All available constraints (e.g. Te/Tp)

See that this is compatible with E_{MAX}~knee
for protons

MAGNETIC FIELD AMPLIF.

Calculate the spectrum obtained at the earth
From a single SNR and many SNRs

Address the issue of chemical composition
Inside the source and at Earth

B-Field amplification

⌘ CR streaming instability (Resonant and non-resonant)

CR induced: works upstream and B advected downstream (Skilling 75, Bell 78, Bell 2004, …)

⌘ Acoustic instability due to grad in the precursor

indirectly induced by CR through the grad (NLDSA)

Drury and Falle 1987

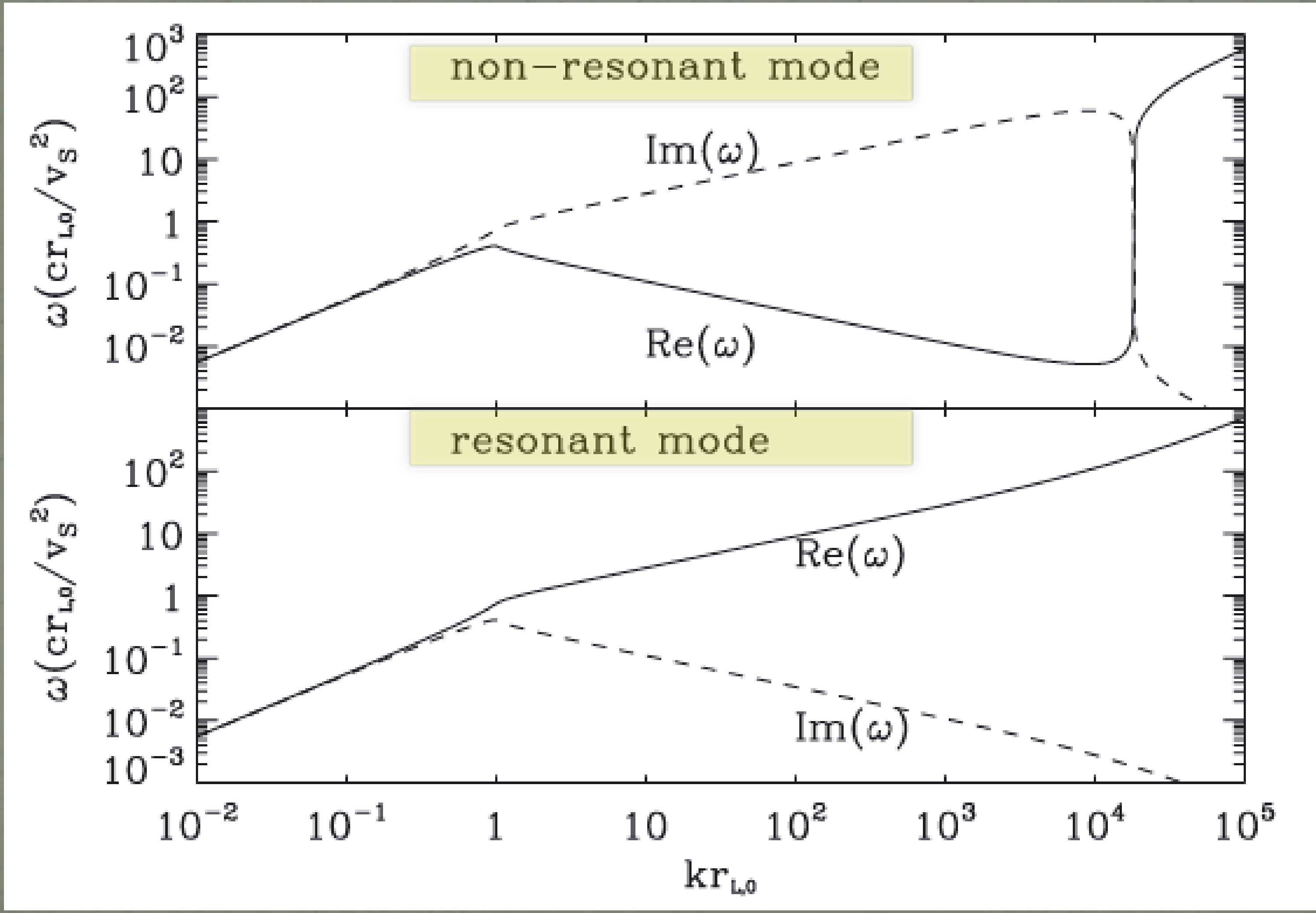
⌘ Firehose instability (Quest and Shapiro 1996)

Might be important if to generate large scale field

⌘ Shock corrugation instabilities (Giacalone & Jokipii 2007)

They operate behind the shock, therefore it does not Appreciably shorten T_{acc} unless the shock is quasi-perp

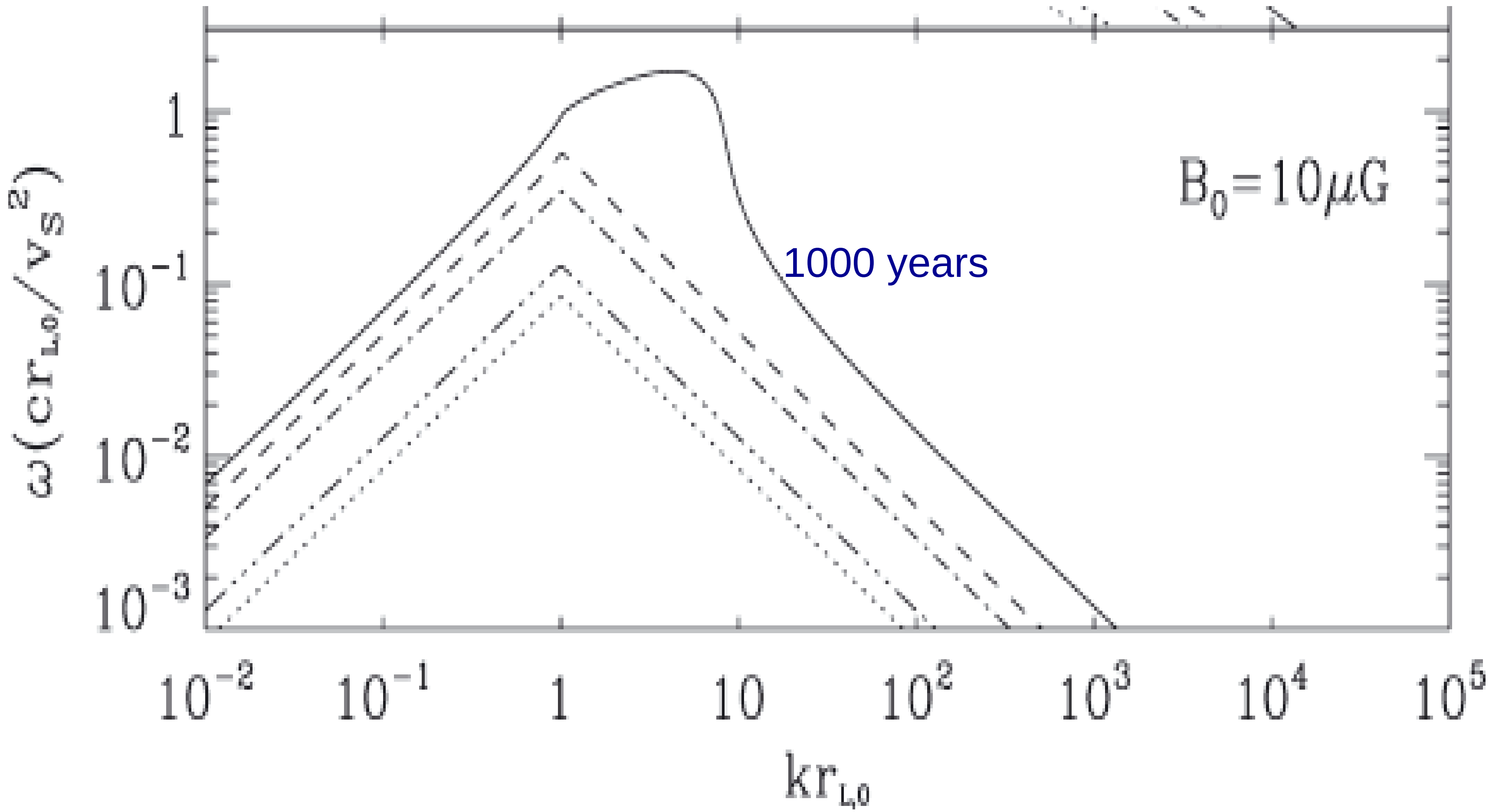
GROWING MODES in CR STREAMING INSTABILITY



Amato & PB 2009, Bell 2004

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

Amato & PB 2009



SATURATION OF GROWTH

Extremely uncertain. It depends on:

a)Damping (type of waves?)

b) Backreaction of fields on the CR current

a) coupling between large and small spatial scales

A naïve extrapolation of QLT would lead to:

$$\frac{\delta B^2}{8\pi} = \frac{1}{M_A}\rho V_s^{\,2}\xi_{CR}$$

in the resonant case, upstream (or possibly δB/B~1 because resonance gets lost)

$$\frac{\delta B^2}{4\pi} = \frac{1}{2}\rho V_s^{\,2}\xi_{CR}\frac{V_s}{c}$$

Estimated analytically from Saturation condition of non resonant Modes (Bell 2004)

Scales

At generation the non res modes at max growth have

$$k_{\max} r_L = \frac{1}{2}\left(\frac{V_s}{V_A}\right)^2 \frac{\xi_{CR}}{\Lambda}\left(\frac{V_s}{c}\right) >> 1$$

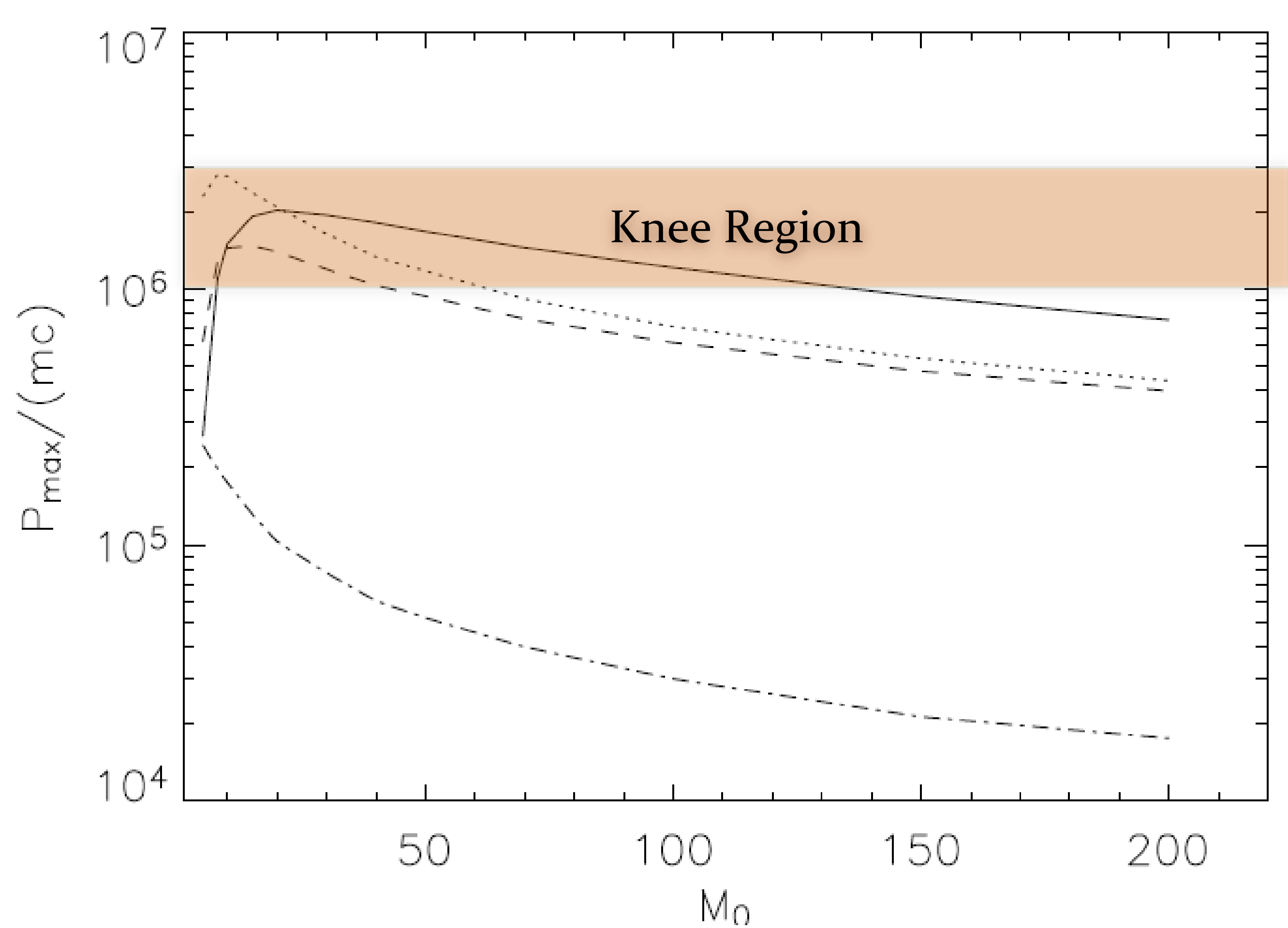
Saturation occur when the particles become magnetized in
The amplified field:

$$\delta B^2 \approx \frac{1}{2}\rho V_s^2\left(\frac{V_s}{c}\right)\frac{\xi_{CR}}{\Lambda}$$

At this point particles scatter effectively because of resonance,
But does this happen sufficiently far from the shock that most
Particles can scatter?

WHY IS IT INTERESTING:
I. Reaching the knee?

PB, Amato & Caprioli, Amato & PB, 2006



$$< t >= -\left[\frac{\partial h}{\partial s}\right]_{s=0} = \frac{3R_{tot}}{u_0^2} \int_{p_{inj}}^{p} \frac{dp'}{p'} \left\{ \frac{R_{tot} D_2(p')}{R_{tot} U_p(p') - 1} + \frac{u_0 \Lambda(p')}{R_{tot} U_p(p') - 1} \right\}$$

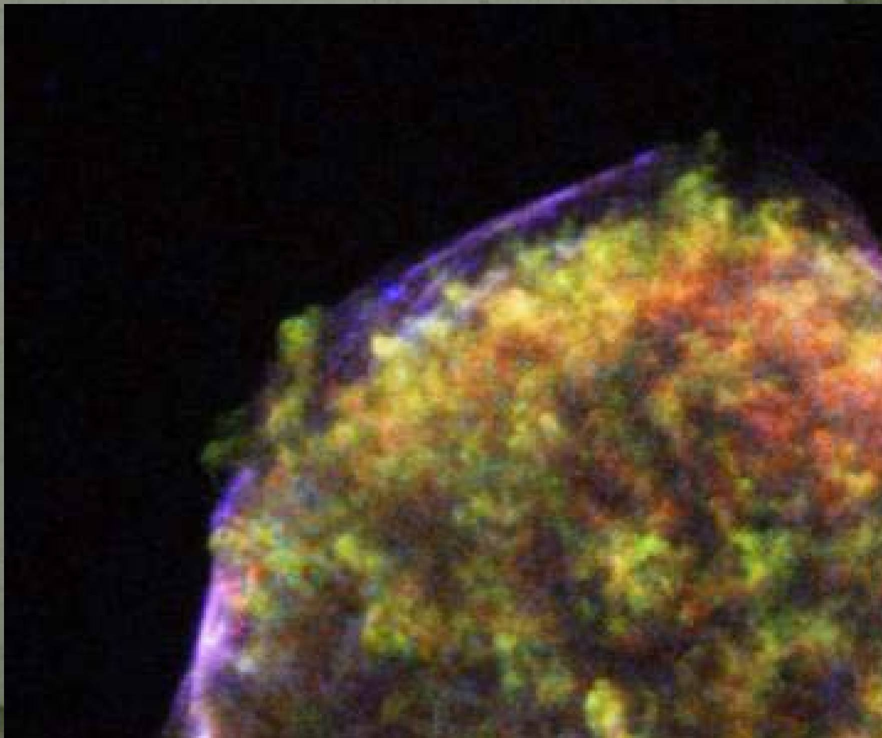
WHY IS IT INTERESTING:
II. Large B observed?

TYPICAL THICKNESS OF FILAMENTS: 10^{-2}

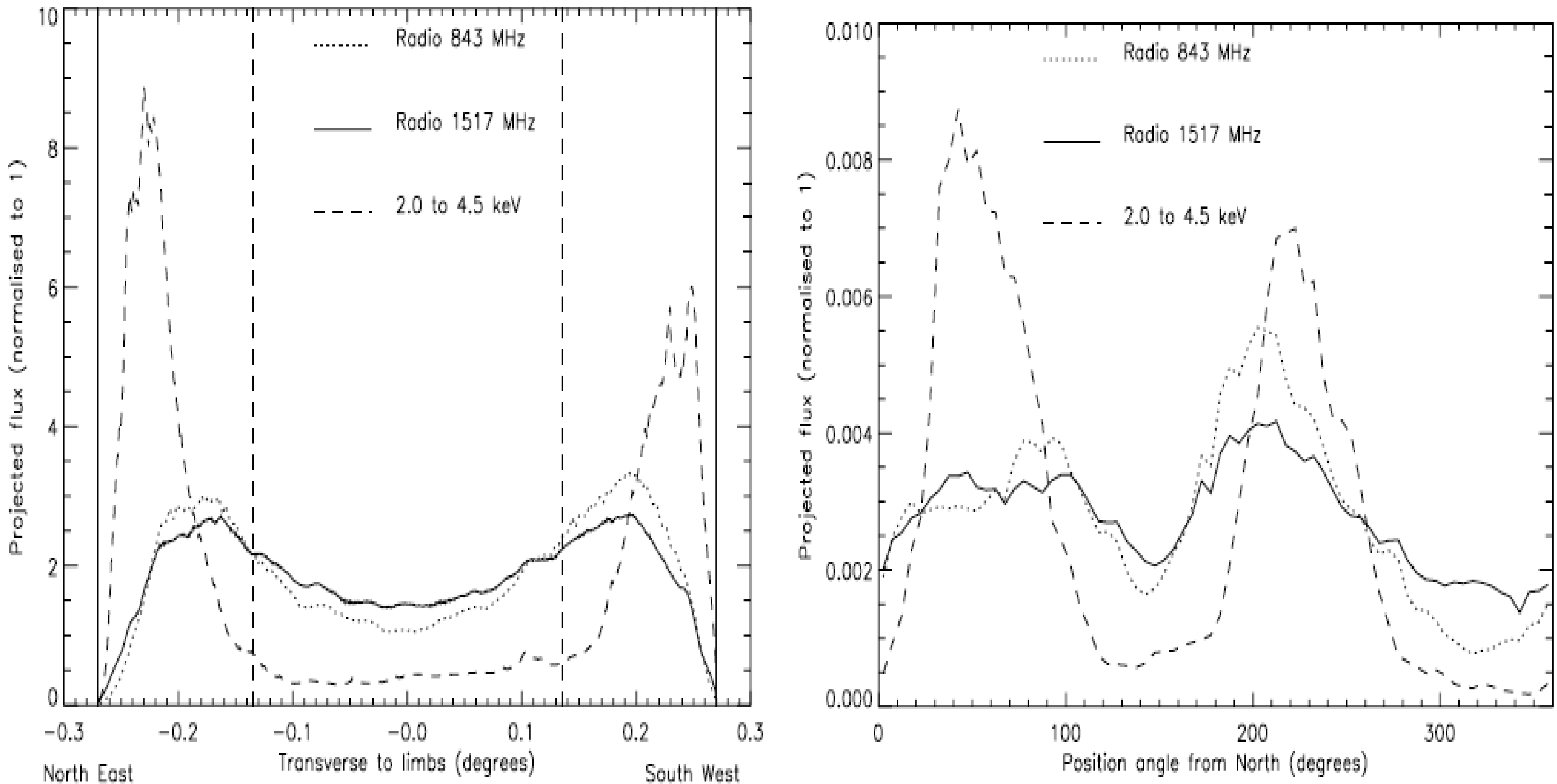
The synchrotron limited thickness is

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

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



FILAMENTS IN RADIO (?)



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

WHAT DO STRONG B DO ?

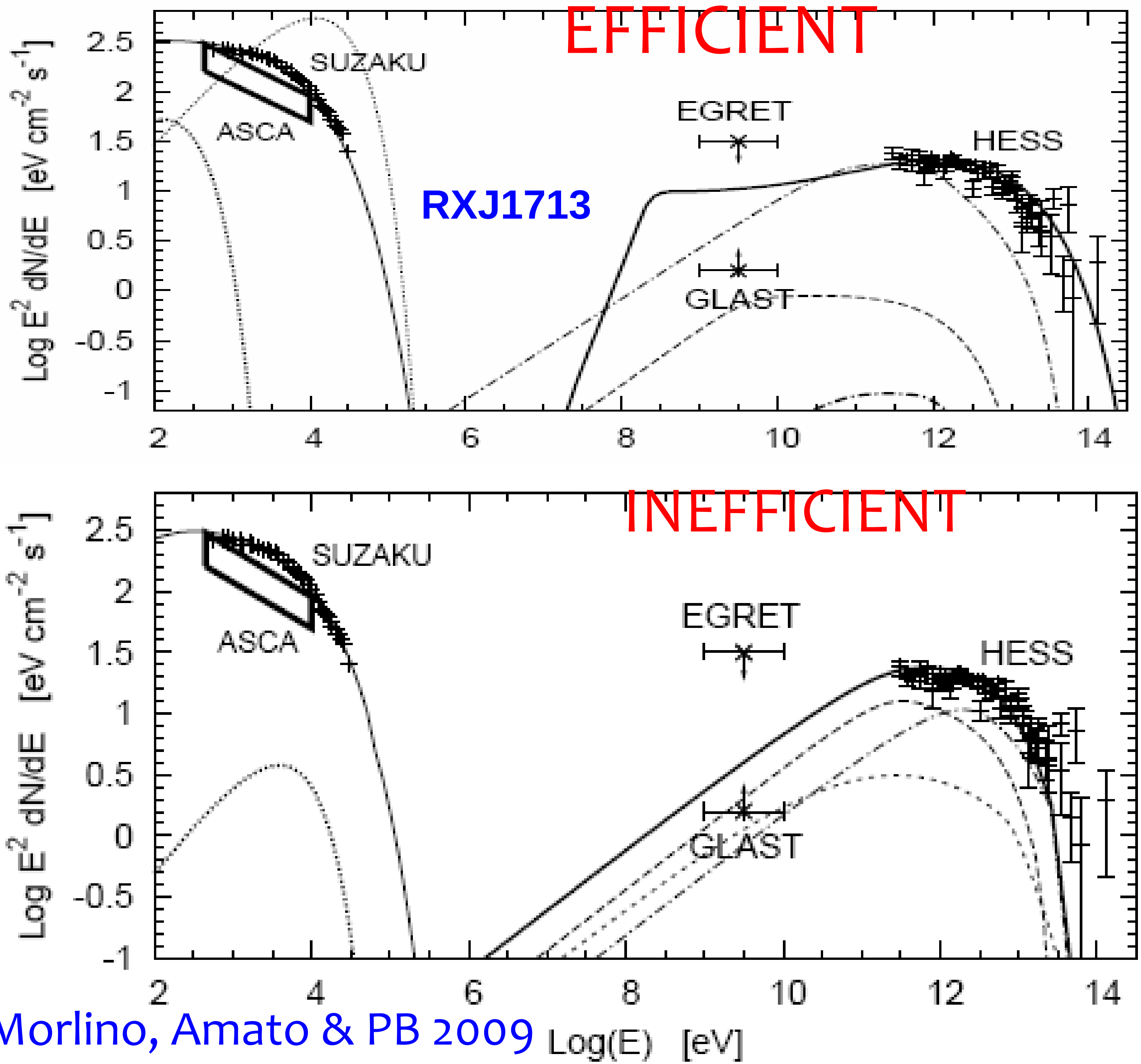
EVEN VERY LARGE B FIELDS HAVE NEGLIGIBLE PRESSU COMPARED WITH THE RAM PRESSURE, BUT WHEN

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

$T_0(\mathrm{K})$	Λ_B	ξ_1	$p_{max}(10^6 GeV)$	R_{sub}	R_{tot}	S_{sub}	S_{tot}	$B_2(\mu G)$	$T_2(10^6\ \mathrm{K})$
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

THE SHOCK MODIFICATION INDUCED BY COSMIC RAYS IS REDUCED

Caprioli, PB, Amato & Vietri 2008, 2009



Morlino, Amato & PB 2009

Problematic points

EFFICIENT ACCELERATION

1. If $T_E=T_P$ overproduction of thermal continuum and possibly line emission
2. $K_{EP}\sim 10^{-4}$ → issue with the electron spectrum at Earth?
3. May be lack of correlation with clouds?

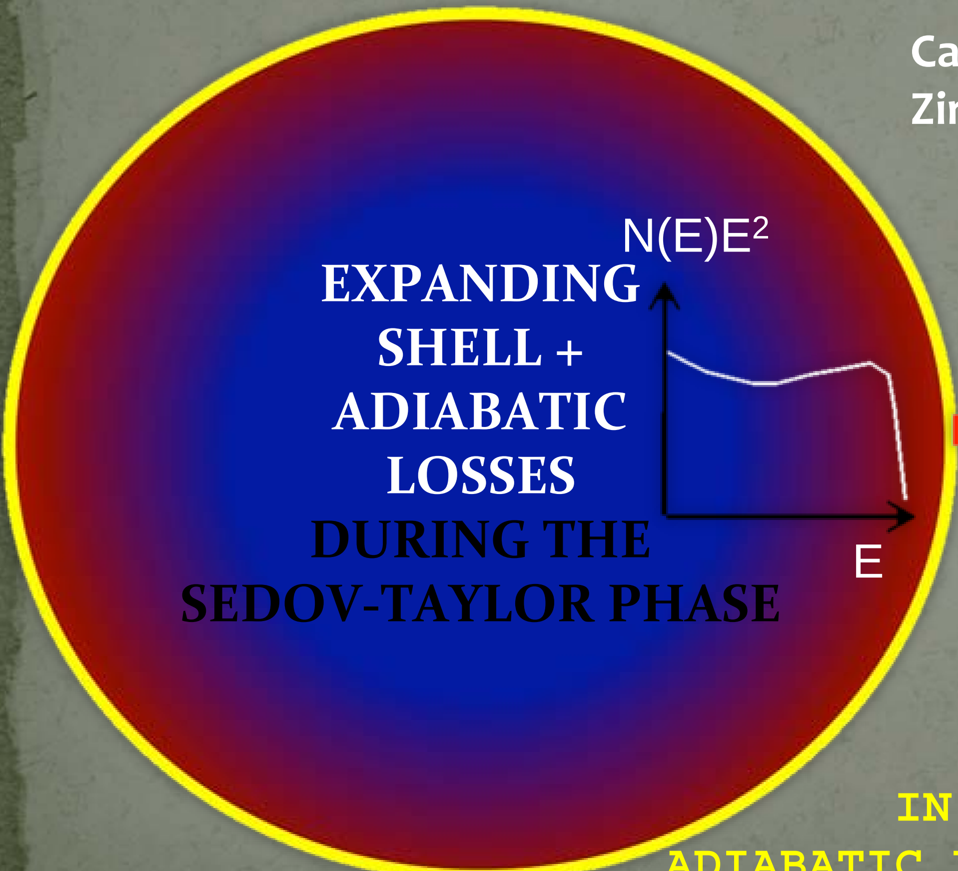
INEFFICIENT ACCELERATION

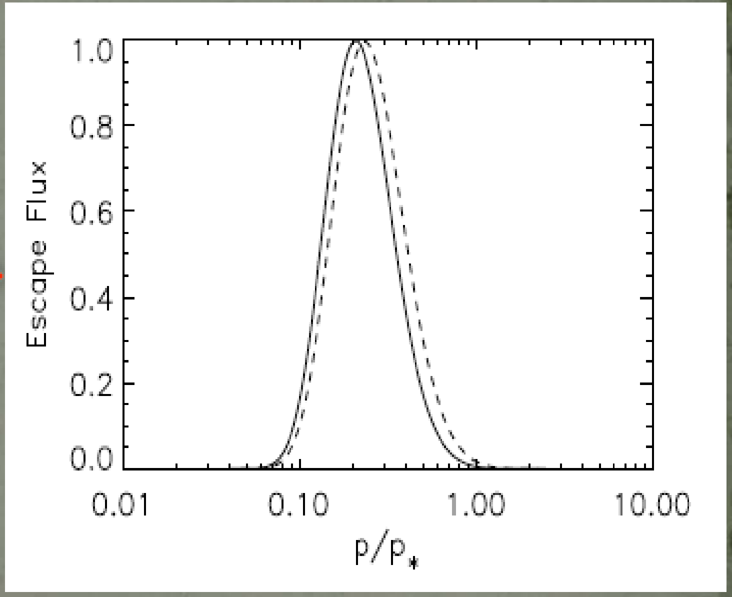
1. The X-ray filaments are not due to B amplif.
2. Last data points in HESS hard to fit
3. Required optical/IR~20 times too big

A MISSING LINK BETWEEN CRs AT EARTH AND ACCELERATED PARTICLES

WHAT IS THE SPECTRUM OF CR AT EARTH?

Caprioli, PB & Amato 2009
Zirakashvili & Ptuskin 2005





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

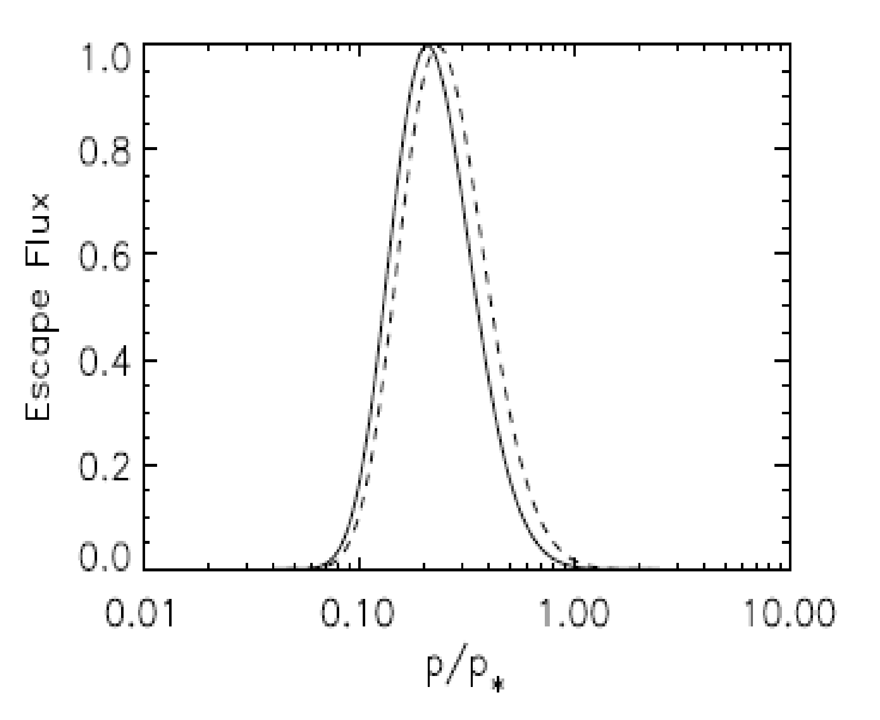
ESCAPE FLUX WITH TIME

Caprioli, PB & Amato 2009; Zirakashvili & Ptuskin 2005

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

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

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



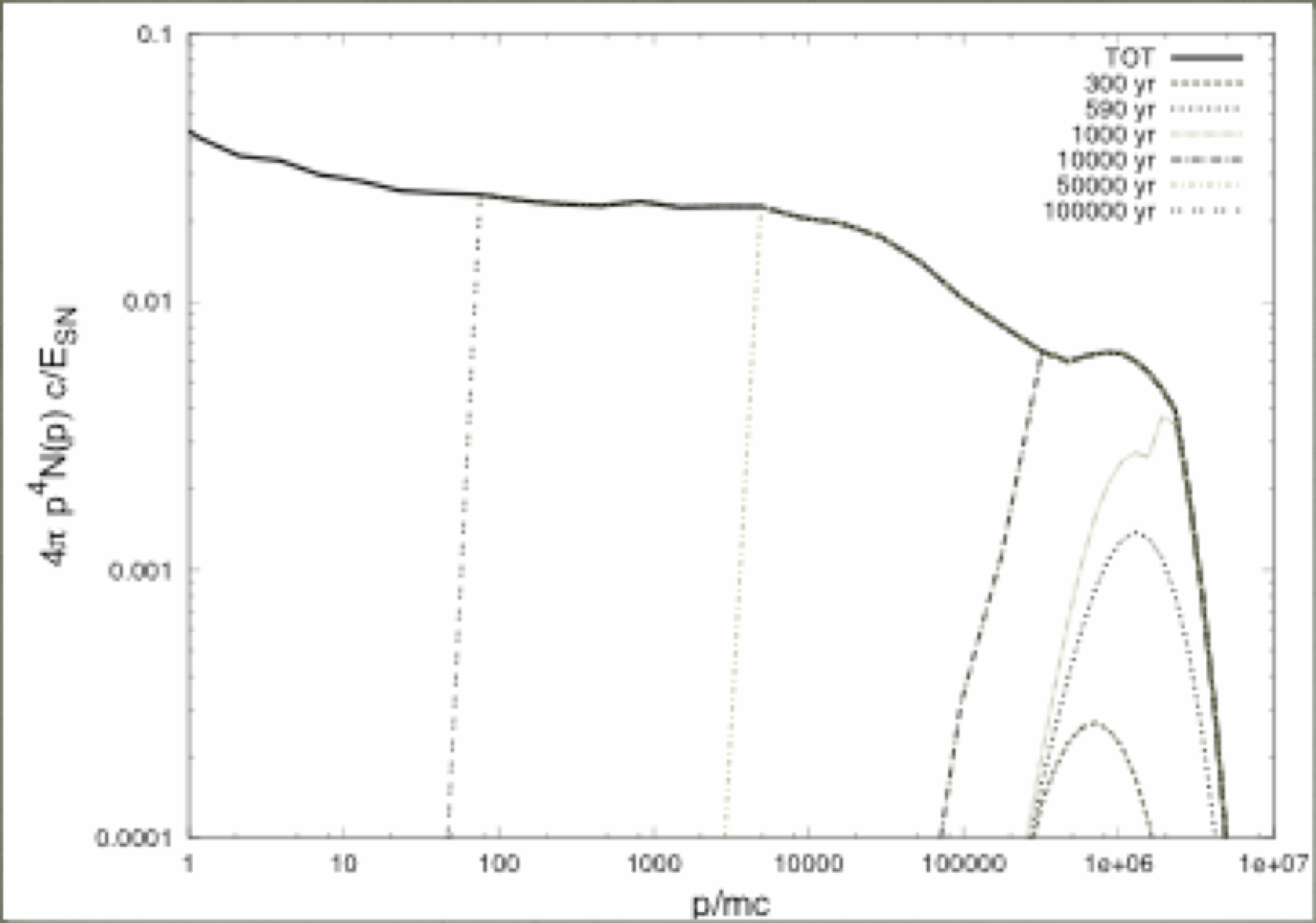
$$Q(E)dE \approx F_{esc}(t)\ \frac{1}{2}\rho V_s^3\ 4\pi R_{sh}^2\ \frac{dE_{max}}{dt}\frac{dE}{E} \propto\ t^{1/2}\ \frac{dE}{E} \propto\ E^{-2}\, dE$$

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

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

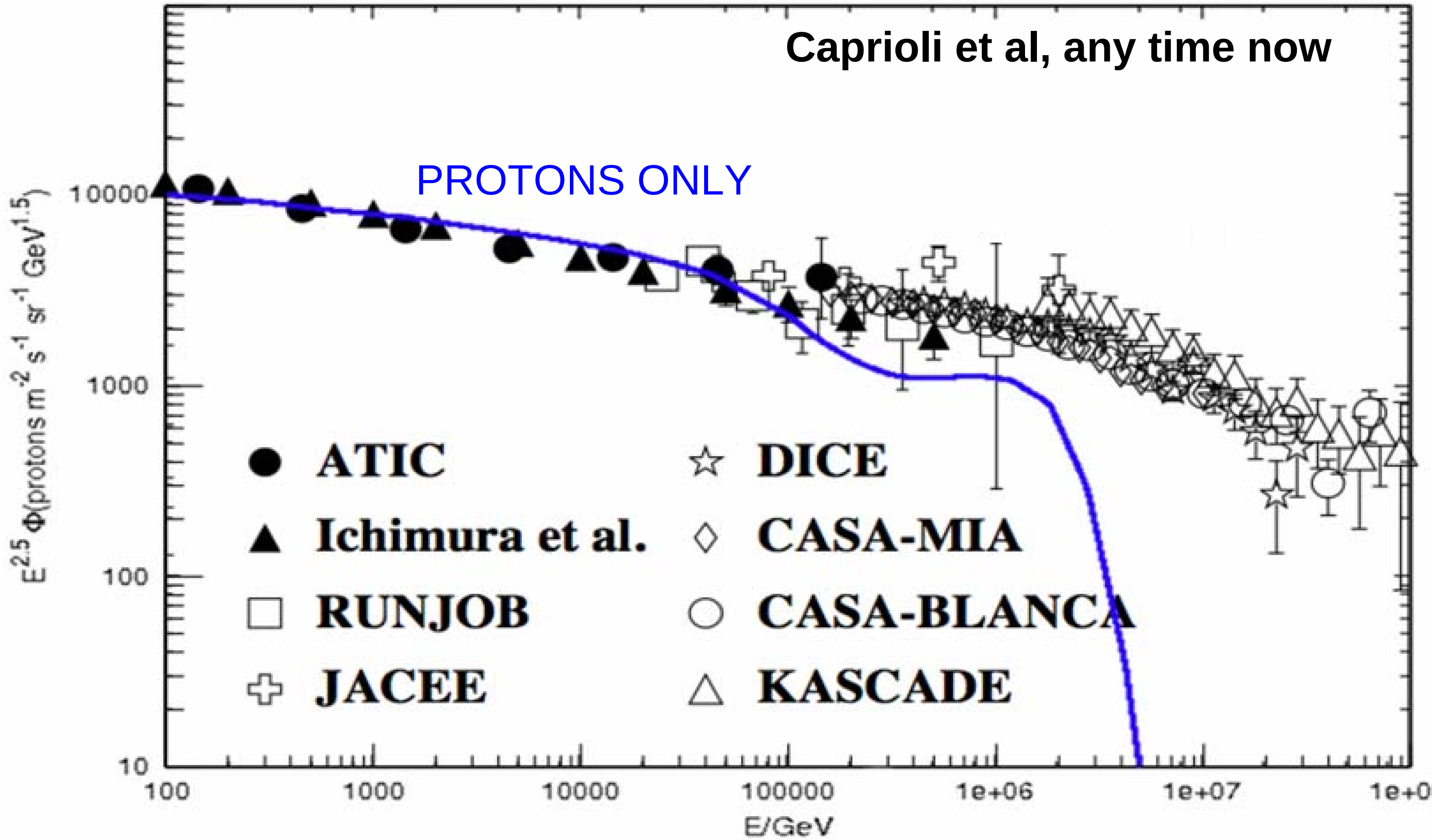
What we see on Earth is the result of the convolution of the Escape time over the sedov-taylor phase of the SNR Evolution, including the crucial effect of **ADIABATIC Energy losses**

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

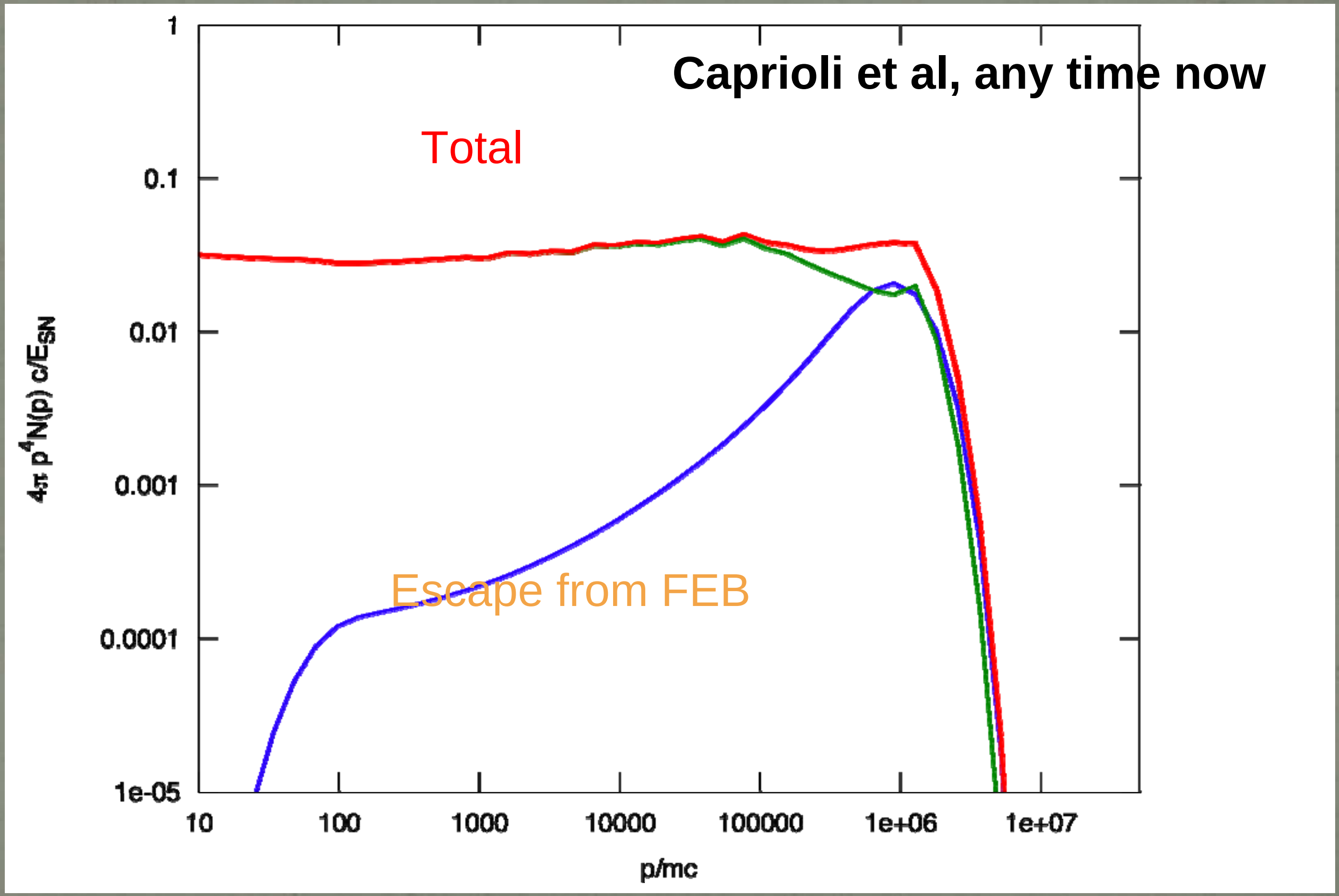


Caprioli et al, any time now

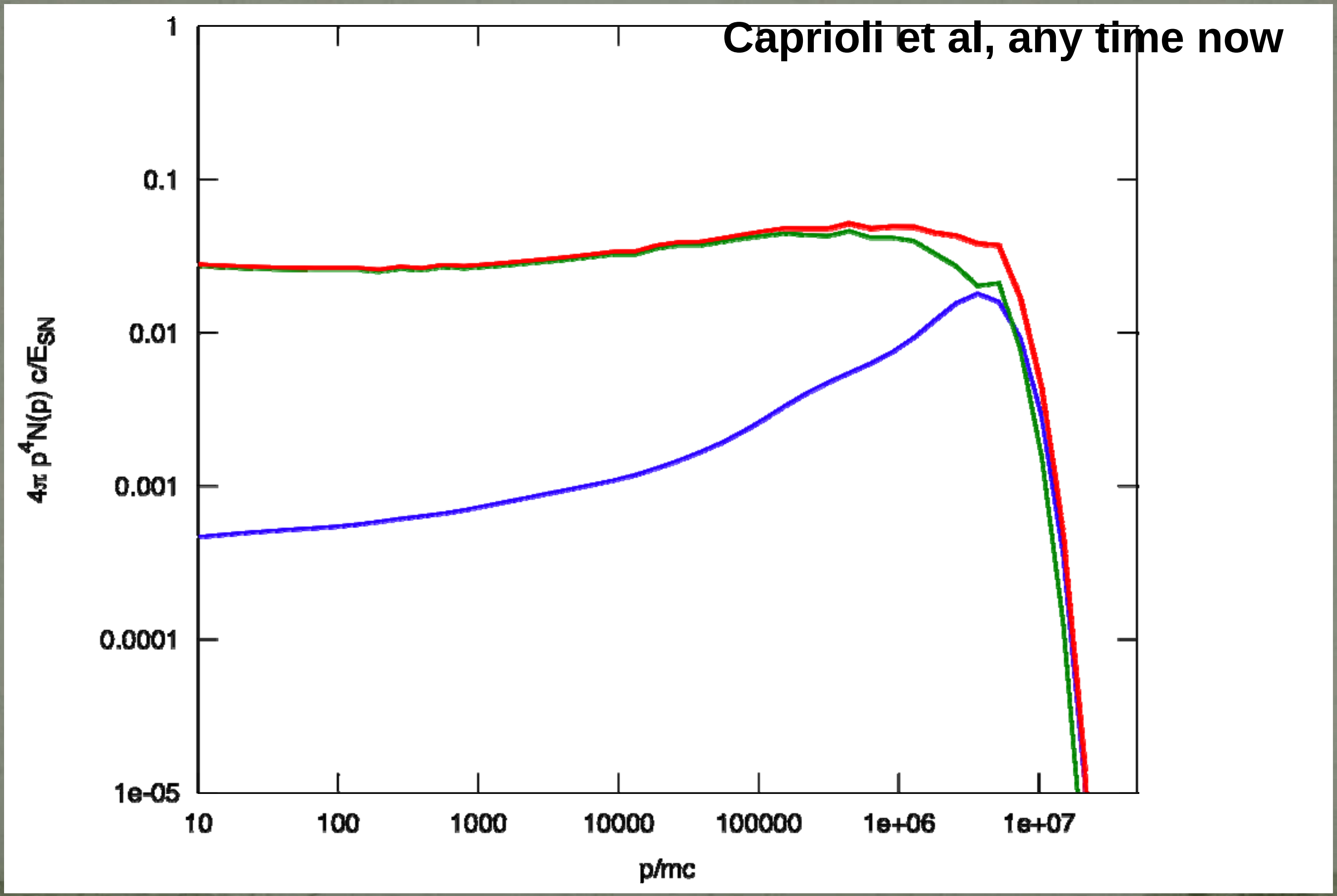
"A" PREDICTED SPECTRUM



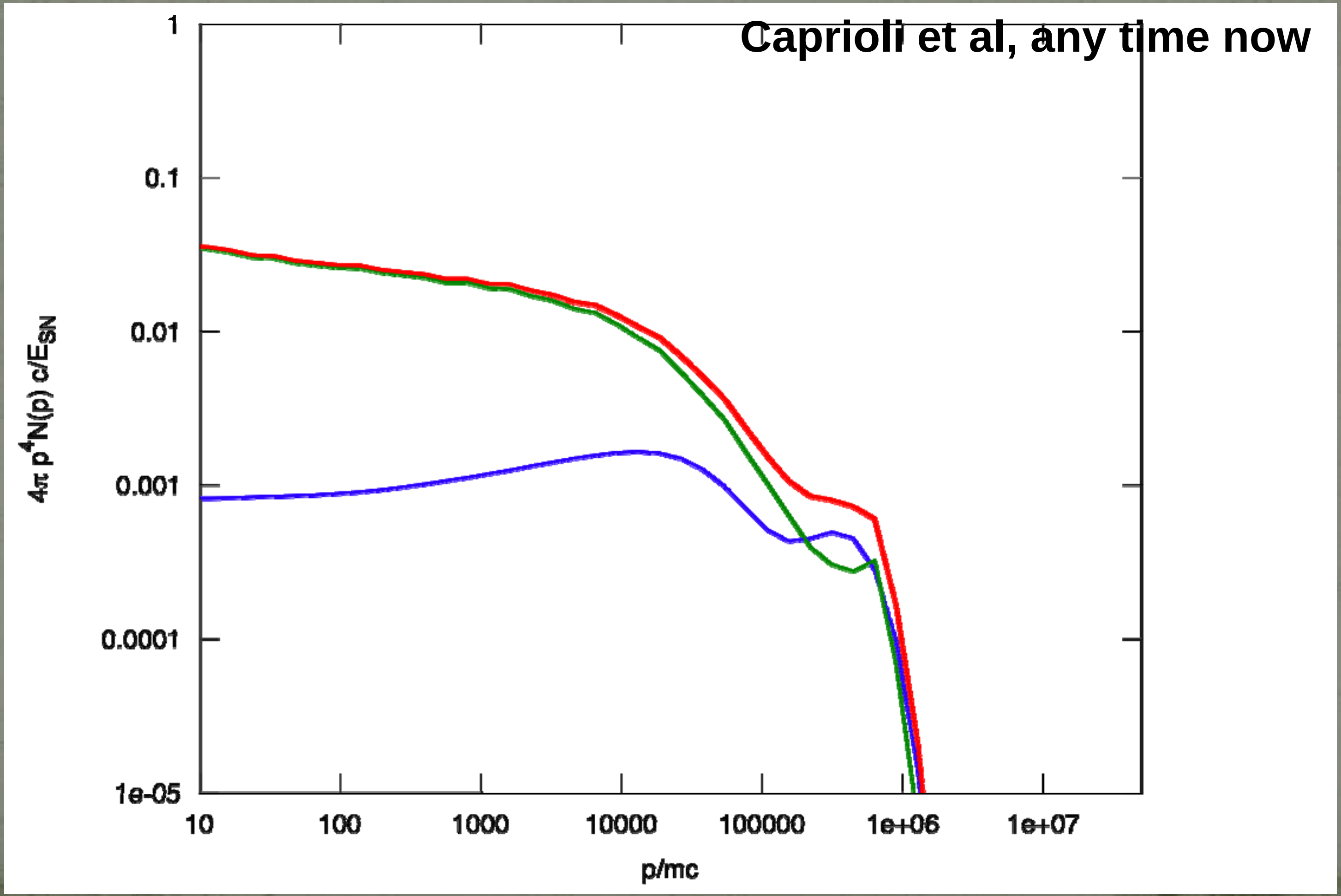
- $T_o=10^5$ K, $n_o=0.1$ cm^{-3}, $B_o=5$ μG, $x_o=0.15$ R_{sh}, Bohm diffusion



- T_o=10^5 K, n_o=0.1 cm^{-3}, B_o=5 μG, x_o=0.15 R_{sh}, Self-generated diffusion



- $T_0=10^5$ K, $n_0=0.1$ cm^{-3}, $B_0=5$ μG, $x_0=0.15$ R_{sh}, Bohm diffusion
- Alfvén velocity in the amplified magnetic field

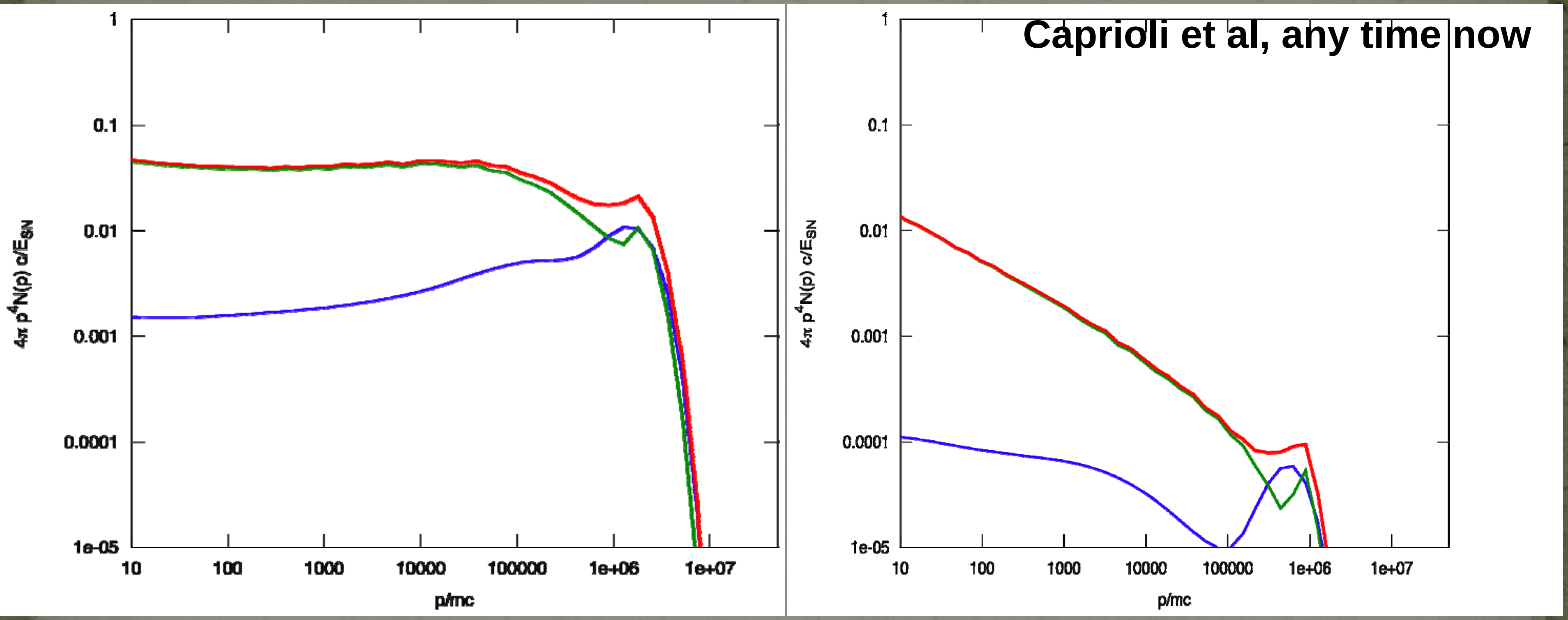


- Type I-like SNR

  $T_o=10^4$ K, $n_o=1$ cm^{-3}

- Type II-like SNR (no winds)

  $T_o=10^6$ K, $n_o=0.01$ cm^{-3}



The total diffuse spectrum of galactic CRs may be the superposition of very different contributions in terms of slope, normalization and composition

A GLOBAL VIEW

ORIGIN IN SNR REQUIRE LARGE EFFICIENCY OF ACCELE

IN GENERAL THIS REQUIRES AND LEADS TO B AMPLIFICA

THE MAX ENERGY IS STILL REACHED AT THE BEGINNING
AND IS AROUND THE KNEE

EFFECTIVE ACCELERATION IN SN-II DOES NOT NECESSA
TO HIGH GAMMA RAY FLUX (WINDS, …)

IN THE CASES IN WHICH WE SEE GAMMA RAYS, IF HADRO
T_e MUST BE $<<T_P$

IN THE SAME CASES, K_{EP} SMALL (COULD IT BE LARGER I

CONFIRMATION OF EFFICIENT ACCELERATION ← DETECTI
THE PRECURSOR

ESCAPE FLUX FROM UPSTREAM IS CRUCIAL TO EVADE ADI
LOSSES AND CONTRIBUTE TO THE KNEE

BUT THE GLOBAL SPECTRUM VERY HARD TO PREDICT (TYP
TYPE II, WINDS, TURBULENT HEATING, TYPE OF WAVES,
SHAPE OF CUTOFFS…) --- BUT TYPICALLY ROUGHLY POWE

NUCLEI ARE YET TO BE INCLUDED IN A SATISFACTORY W
IT MAKES SENSE THAT THE GALACTIC CR SPECTRUM MAY
AROUND ~$10^{17.5}$ eV WITH HEAVY COMPOSITION