PARTICLE ACCELERATION IN ASTROPHYSICAL SHOCKS
AND
THE ORIGIN OF COSMIC RAYS

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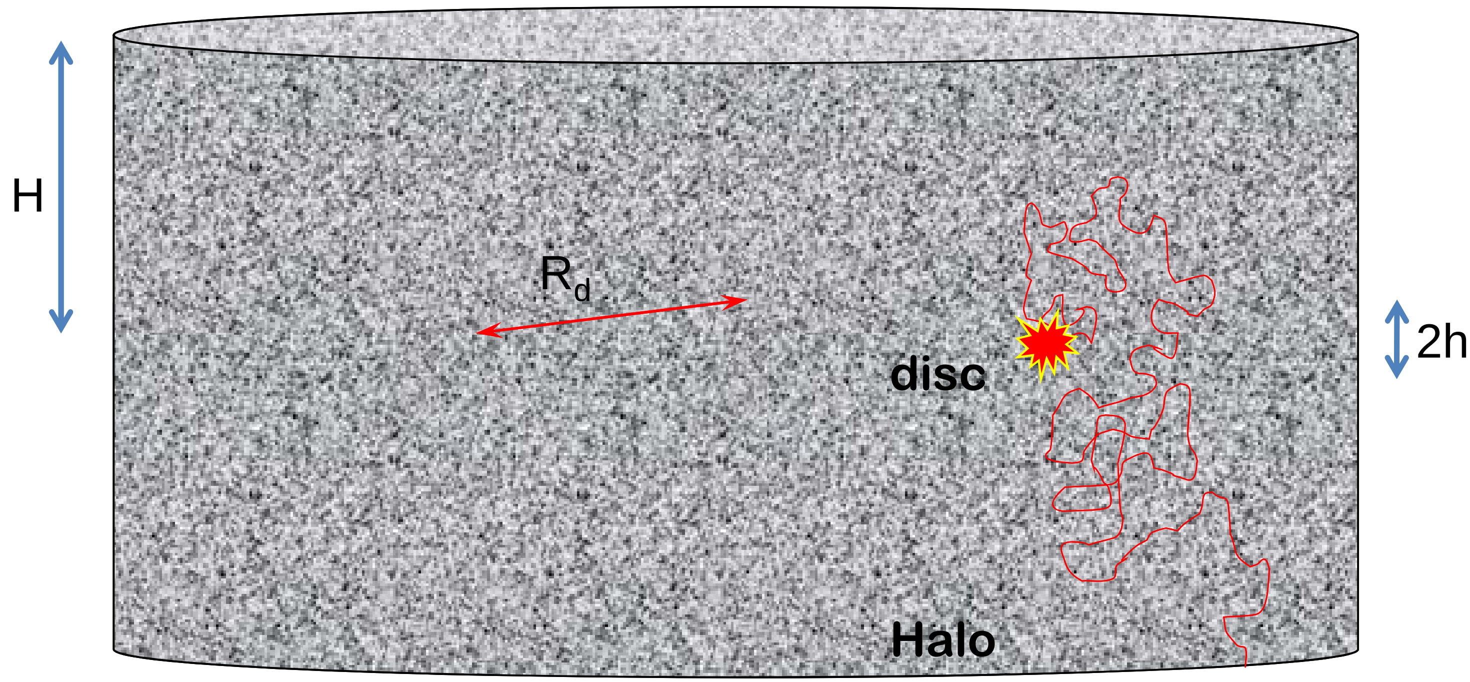
CR Acceleration at shocks

DIFFUSIVE SHOCK ACCELERATION

SUPERNOVA PARADIGM FOR THE ORIGIN OF COSMIC RAYS

TEST PARTICLE DIFFUSIVE SHOCK ACCELERATION

- POWER LAW SPECTRA
- THE SLOPE IS ONLY DEPENDENT UPON THE COMPRESSION FACTOR AT THE SHOCK
- THE SPECTRUM FOR STRONG SHOCKS IS ASYMPTOTICALLY E^{-2}
- NO EASY WAY TO DETERMINE MAXIMUM ENERGY
- BUT WHEN ESTIMATED USING THE GALACTIC D(E) $\rightarrow$ E_{MAX}~GeV



Particle escape

In general: R_d > H >> h

ASSUMPTIONS:

1. Instantaneous injection of particles in a point in the disc
2. Infinitely thin disc, h ➔ 0 and infinitely extended disc, R_d➔
3. Free escape of the particles from above and below the halo $n(z=\pm H, r, E)=0$

$$n_{CR}(E)=\int_0^\infty d\tau\int_0^{R_d} dr\,2\pi\,\mathrm{r}\;\frac{\mathrm{N(E)}\,\Re}{\pi\,\mathrm{R_d^2}}\,\Im(z=0,r=0,x=y=0)=\frac{\mathrm{N(E)}\,\Re}{2\pi\,\mathrm{D(E)}\,\mathrm{R_d}}\;\frac{\mathrm{H}}{\mathrm{R_d}}$$

The Supernova remnant paradigm in numbers

Let us assume that the rate of SN in the Galaxy is $\mathscr{R}$ and each produces a power law spectrum of protons $N(E)=K\,(E/E_0)^{-\gamma}$ and we take E_0~m~1 GeV

$$E_{CR} = \int dE N(E) E = \frac{K}{\gamma-2} = \xi_{CR} E_{SN} \Rightarrow K = (\gamma-2)\xi_{CR} E_{SN}$$

Order 10^{51} erg

and energies are taken to be normalized to E_0.

The observed spectrum of protons at Earth is $\phi(E) = c n_{CR}(E)/(4\pi)$
and taking $D(E) \sim (\rho/3GV)^{\delta}$ where ρ is the rigidity

$$\phi_{CR}(E) \approx 2.4 E_{51} \xi_{CR} R_{d,15}^{-2} \mathcal{R}_{SN,30} (\gamma-2) 3^{\delta} E_{TeV}^{-2.73} TeV^{-1} m^{-2} s^{-1} sr^{-1}$$

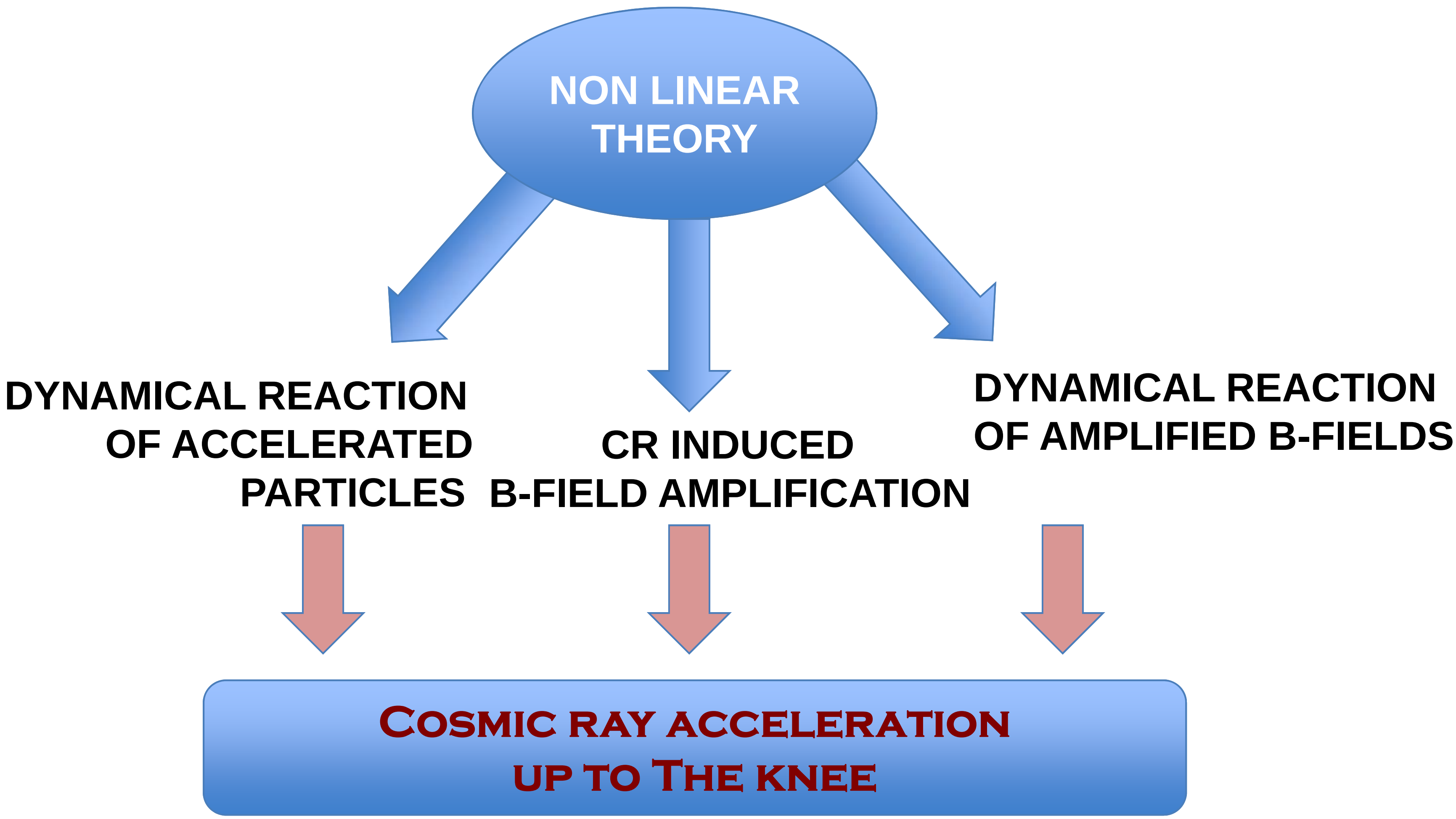
and comparing with the observed spectrum $8.7 \times 10^{-2} E_{TeV}^{-2.73} TeV^{-1} m^{-2} s^{-1} sr^{-1}$

$$\xi_{CR} \sim 7\% \text{ for } \delta = 1/3$$
$$\xi_{CR} \sim 11\% \text{ for } \delta = 0.54$$
$$\xi_{CR} \sim 58\% \text{ for } \delta = 0.7$$

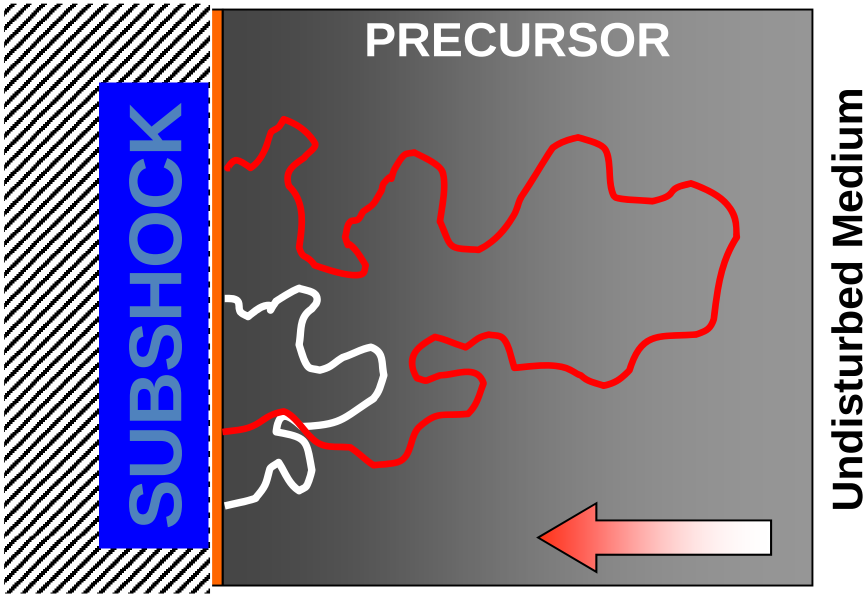
Relatively large efficiencies required

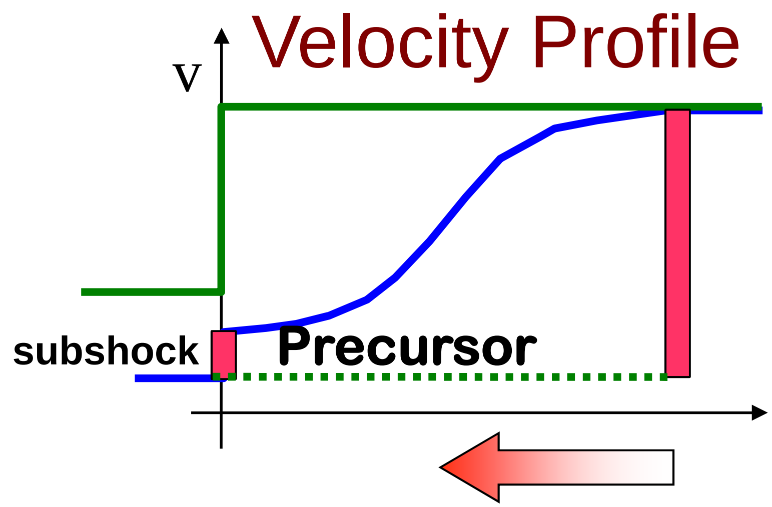
BEYOND TEST PARTICLES: *Non linear DSA*

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



Dynamical Reaction of Accelerated Particles



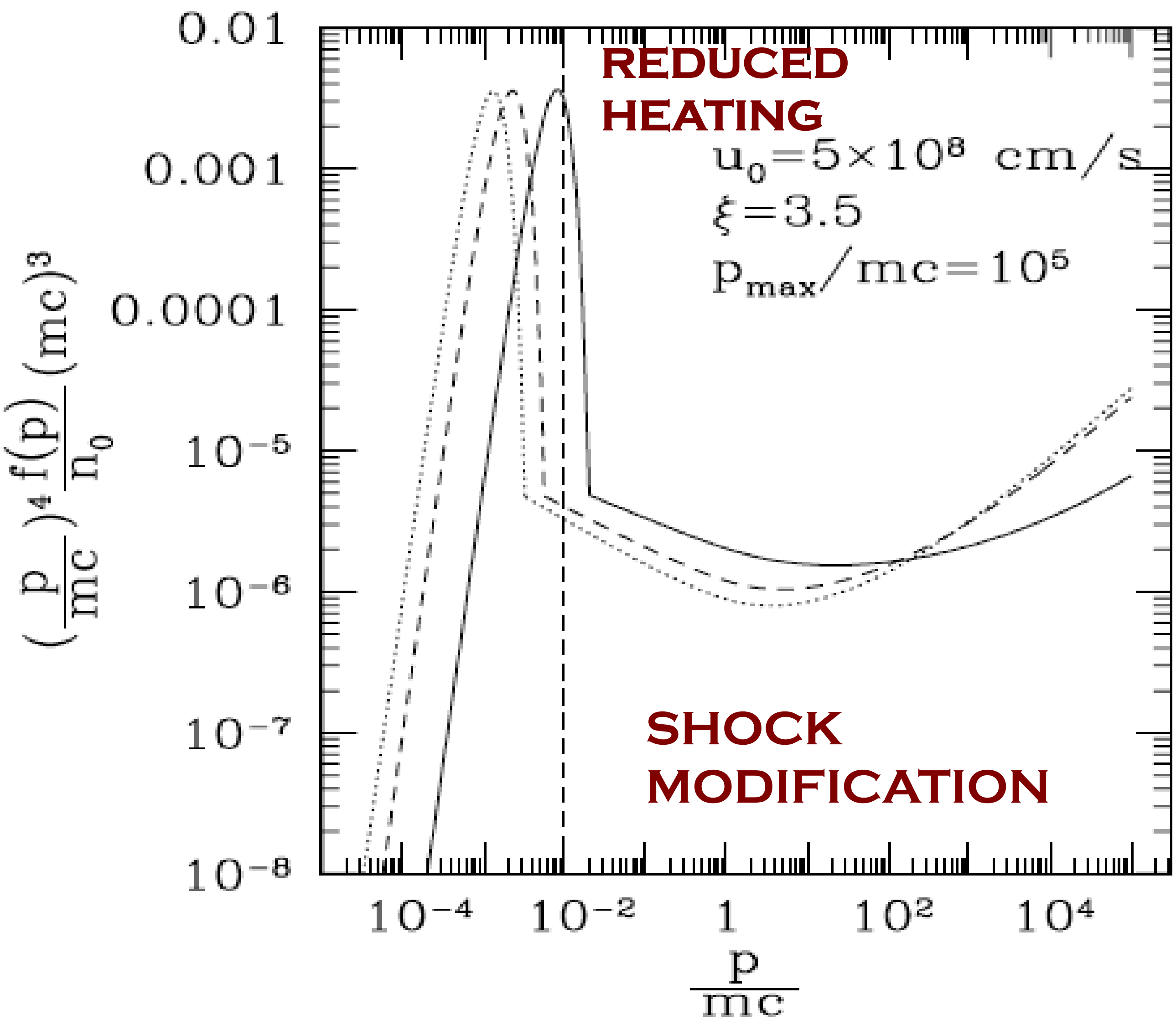


Conservation of Mass, Momentum and Energy +

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

Transport equation for cosmic rays

SHOCK HEATING and SPECTRA



PB, Gabici & Vannoni 2005

COSMIC RAY INDUCED MAGNETIC FIELD AMPLIFICATION

RESONANT GROWTH (Bell 78, Skilling 75, Lagage & Cesarsky 83)

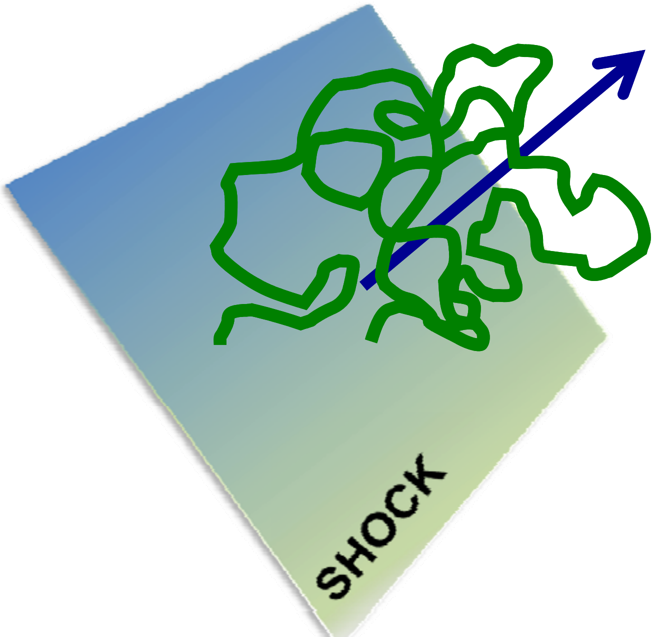
Alfven waves grow in resonance with diffusing particles which resonantly scatter on them (growth and scattering are naturally on the same scale)

NON-RESONANT GROWTH

Bell 04 discussed a non resonant way to grow (non-Alfvenic) waves with λ<<gyration radius → no efficient scattering unless inverse cascade

Other instabilities (e.g. firehose) lead to λ>>gyration radius (still non resonant)

MAGNETIC FIELD AMPLIFICATION



Bell 2004, Amato & PB 2009

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

PARTICLES ARE ACCELERATED BECAUSE THERE IS HIGH MAGNETIC FIELD IN THE ACCELERATION REGION

HIGH MAGNETIC FIELD IS PRESENT BECAUSE PARTICLES ARE ACCELERATED EFFICIENTLY

WITHOUT THIS NON-LINEAR PROCESS, NO ACCELERATION OF CR TO HIGH ENERGIES (AND ESPECIALLY NOT TO THE KNEE!)

Successes of the SNR paradigm
1. Observation of X-ray rims

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

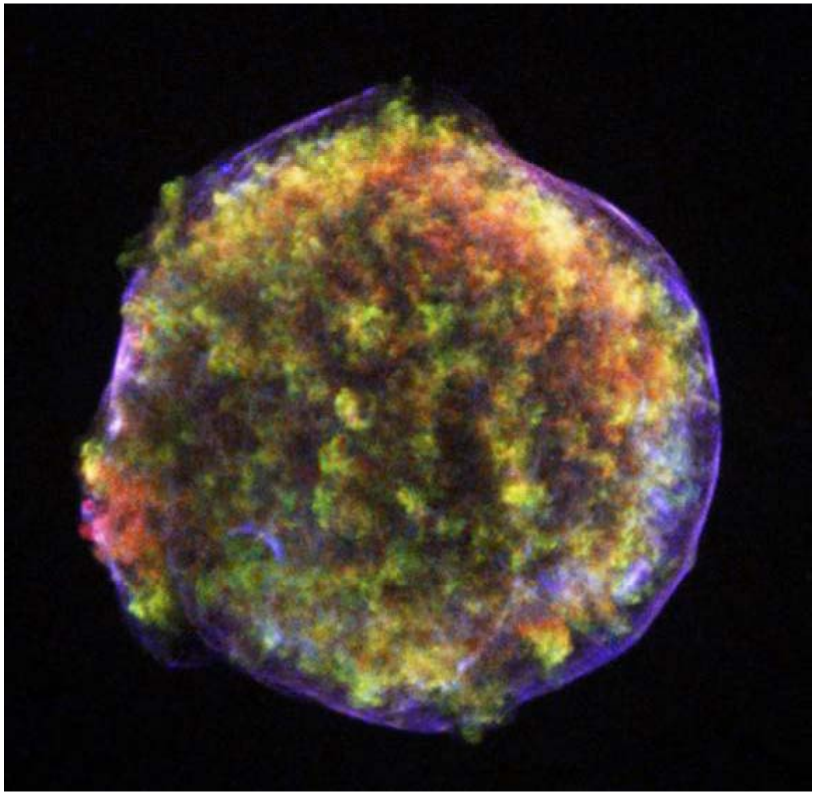
The synchrotron limited thickness is:

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

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

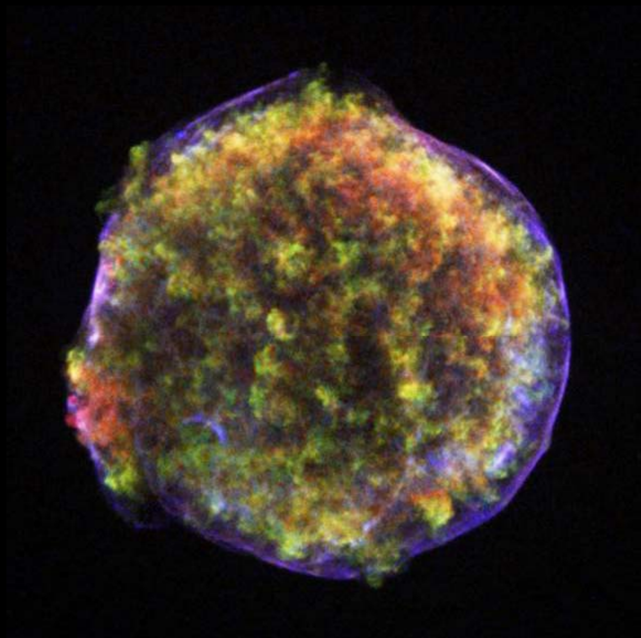
$$E_{max} \approx 10\ B_{100}^{-1/2}\ u_8\ \mathrm{TeV}$$

$$\nu_{max} \approx 0.2\ u_8^2\ \mathrm{keV}$$



In some cases the strong fields are confirmed by time variability of X-rays

Uchiyama & Aharonian, 2007



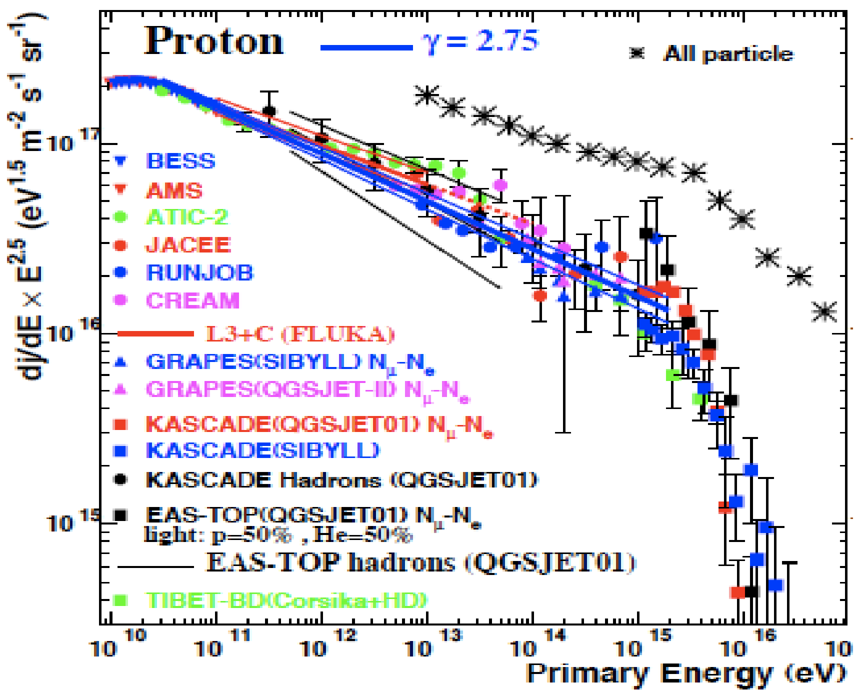

Chandra
Cassiopeia A


Chandra
SN 1006

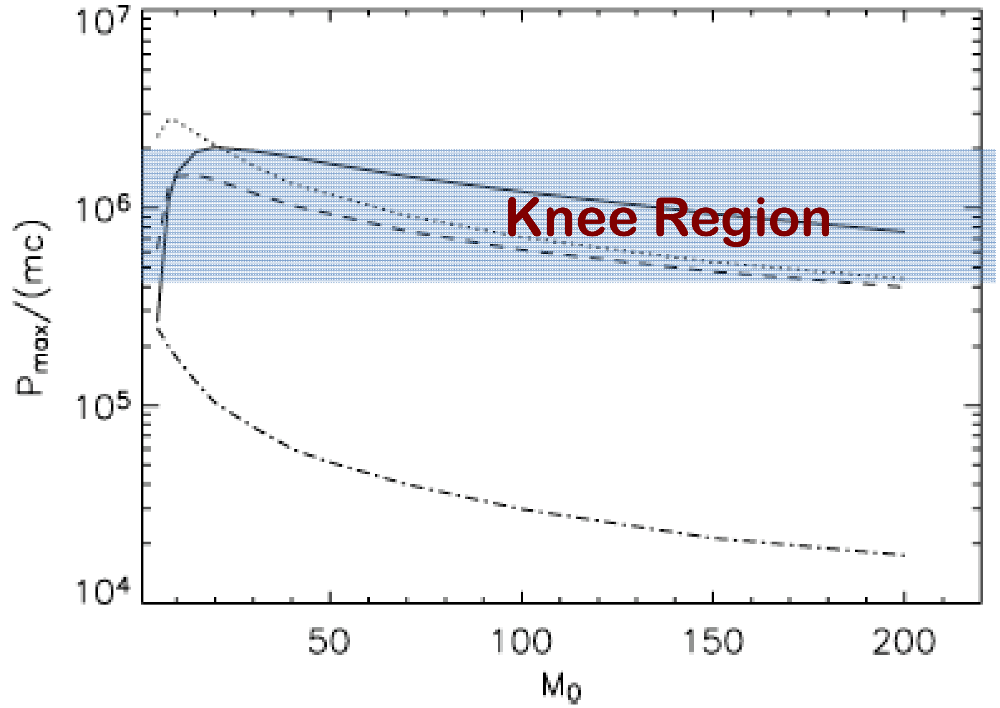
Successes of the SNR paradigm

2. Max energy and the knee

Magnetic field amplification leads to higher values of the Maximum energy



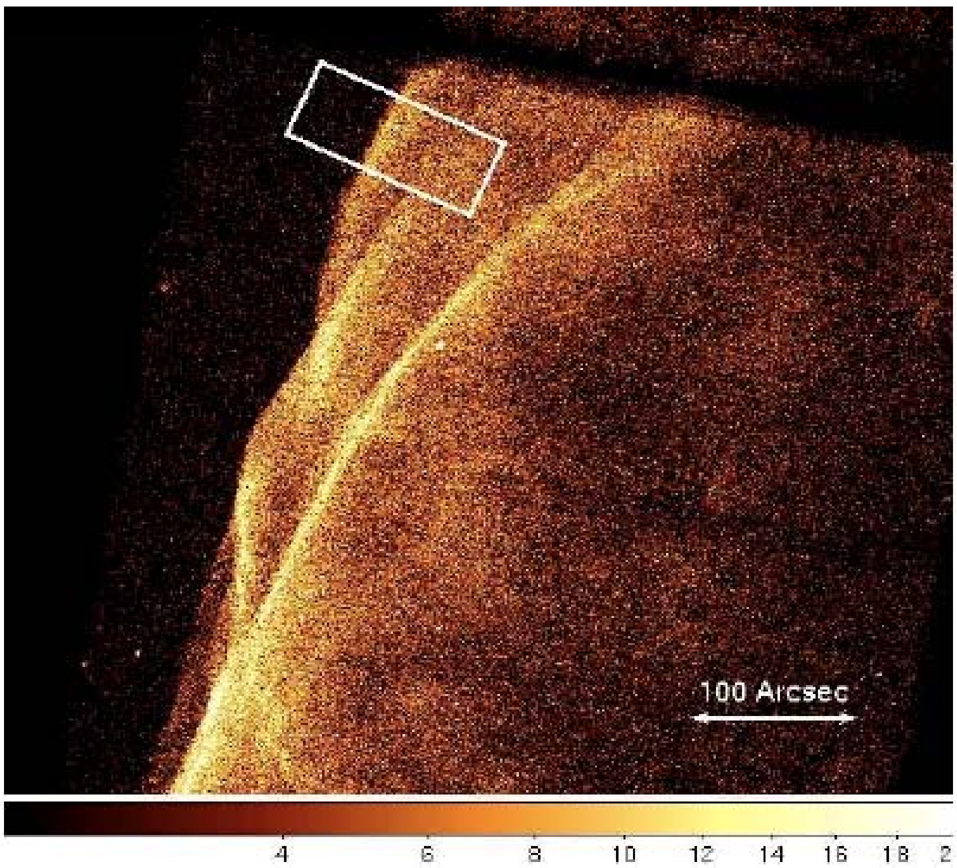
Data from Bertaina et al. 2008



PB, Amato & Caprioli, 2007

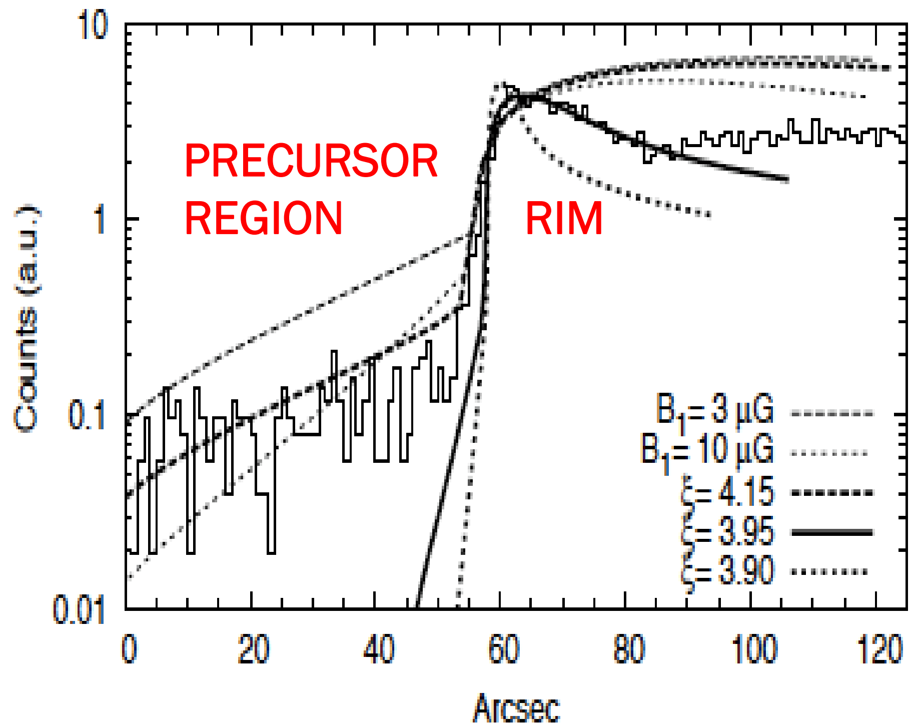
Successes of the SNR paradigm

3. evidence for a CR precursor ?



Morlino, Amato, PB & Caprioli 2010

ξ	B_1 (μG)	B_2 (μG)	R_{sub}	R_{tot}
3.90	47	175	3.78	6.39
3.95	23	90	3.93	5.53
4.15	5.3	21	4.00	4.08
∞	3.0	10	4.00	4.00
∞	10	33	4.00	4.00



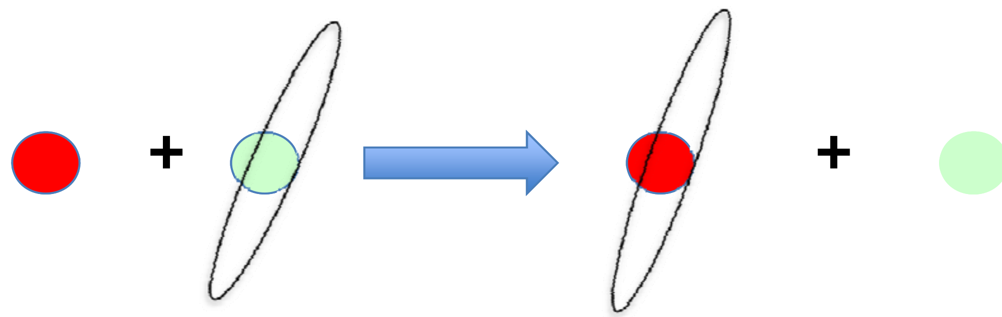
Successes of the SNR paradigm

4. Balmer dominated shocks

DOWNSTREAM

ION Temperature LOWER because of CR acceleration

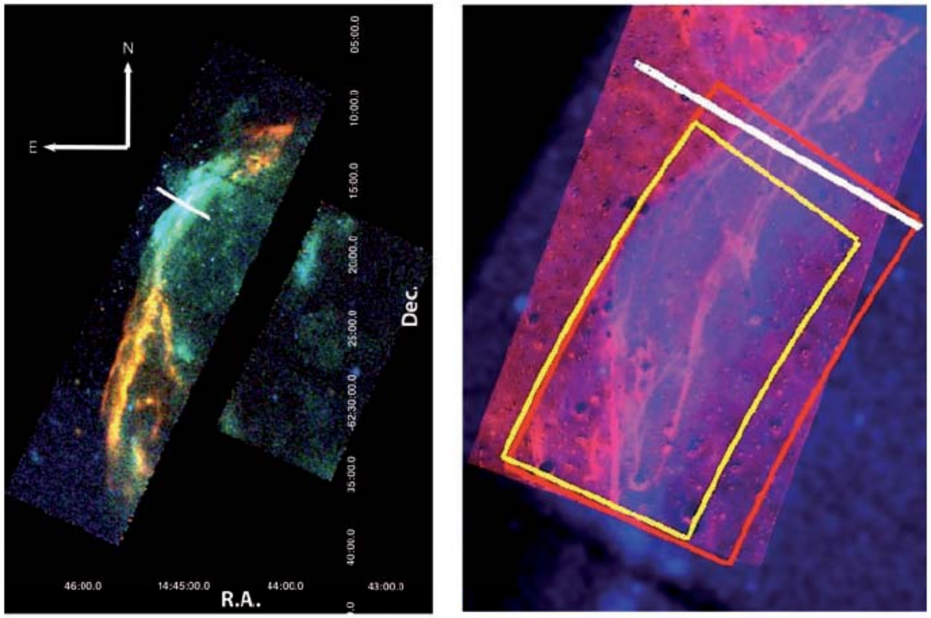
NEUTRAL Temperature HIGHER because of charge exchange

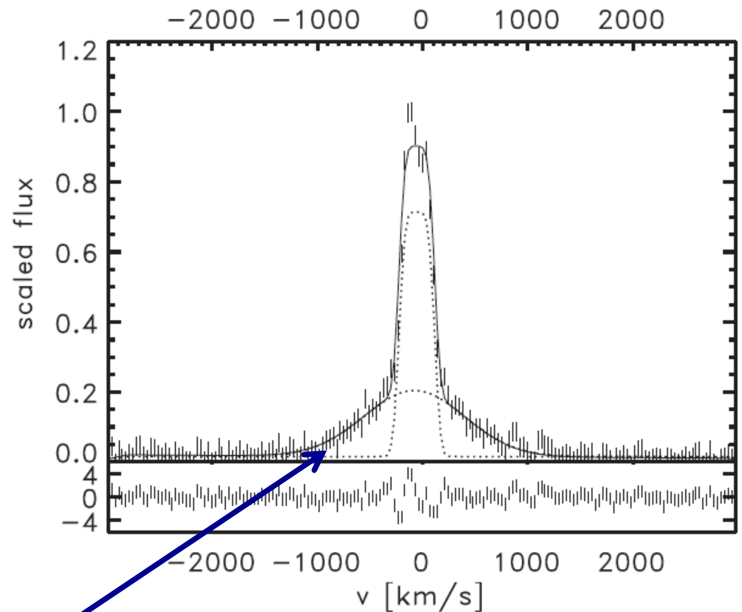


BROAD BALMER LINE IS NARROWER

NARROW BALMER LINE IS WIDER

OBSERVATIONS OF BALMER DOMINATED SHOCKS





Helder et al. 2009

$$W_{broad} = 1100 \pm 63\, km/s \;\rightarrow\; T_2 = 2.3 \pm 0.3\, keV$$

Shock speed from proper motion

$$v_{shock} = 6000 \pm 2800\, km/s \left(\frac{d}{2.5 \pm .5\, kpc}\right)\left(\frac{\dot{\theta}_{obs}}{0.5 \pm .2''\, yr^{-1}}\right) \rightarrow T_2 = \begin{matrix} 20-150\, keV\, (no\ equilibration) \\ 12-90\, keV\, (equilibration) \end{matrix}$$

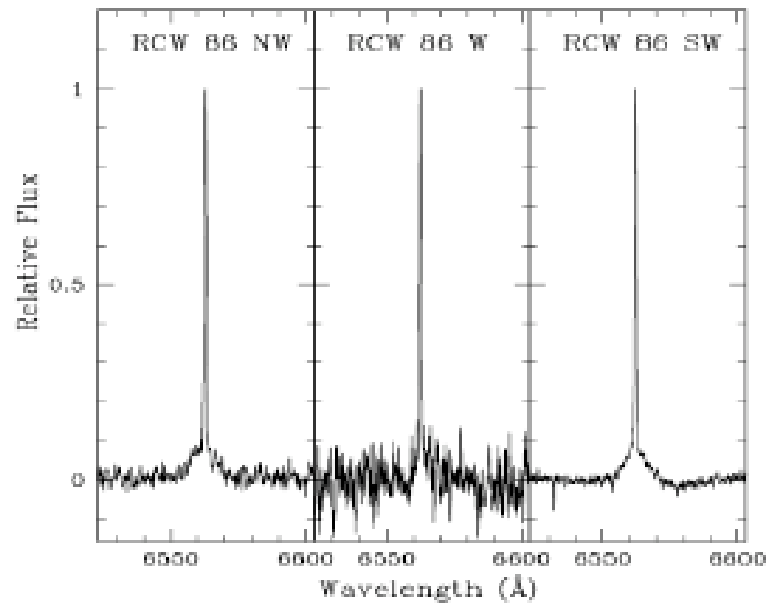
INFERRED EFFICIENCY of CR ACCELERATION 50-60% !!!

OBSERVATION OF BALMER DOMINATED SHOCKS

broader narrow Balmer line

Sollerman et al. 2003

SNR	Shock velocity (km s^{-1})	Narrow component *FWHM* (km s^{-1})
Cygnus Loop	300–400	28–35
RCW 86 SW	580–660	32 ± 2
RCW 86 W	580–660	32 ± 5
RCW 86 NW	580–660	40 ± 2
Kepler D49 & D50	2000–2500	42 ± 3
0505-67.9	440–880	32–43
0548-70.4	700–950	32–58
0519-69.0	1100–1500	39–42
0509-67.5	–	25–31
Tycho	1940–2300	44 ± 4
SN 1006	2890 ± 100	21 ± 3



$$W_n \sim 30-50\, km/s \rightarrow T \sim 2-6\, 10^4\, K$$

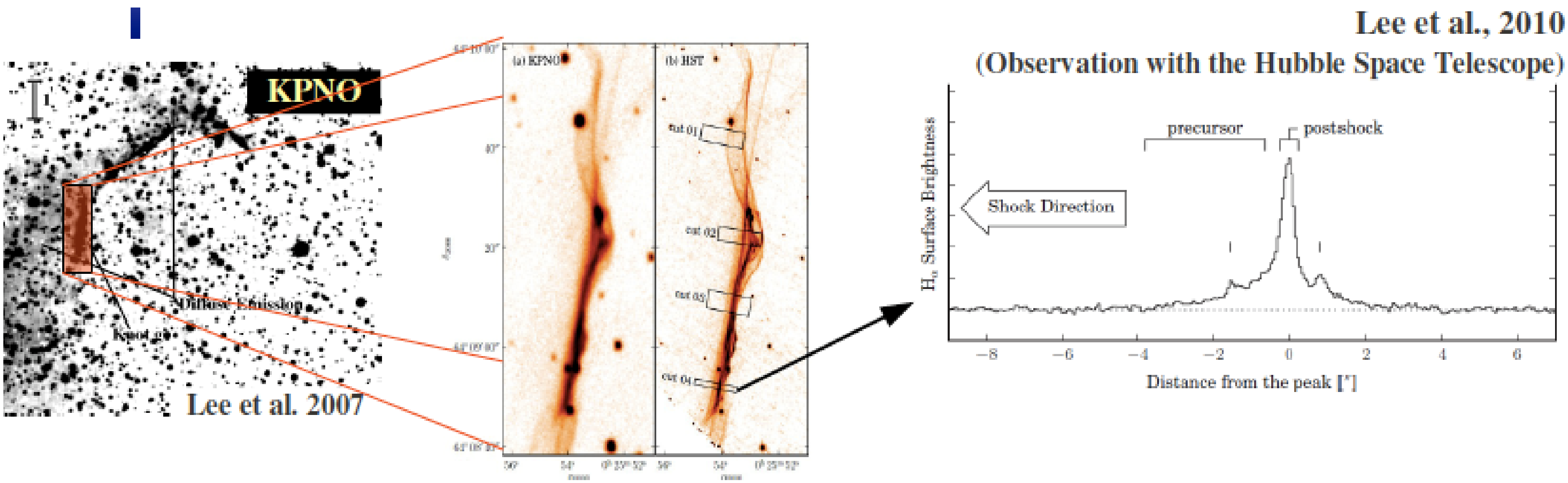
Broadening of the narrow line hints to a mechanism for heating of the <u>neutrals</u> upstream on scales shorter than ionization scales

TURBULENT HEATING

CHARGE EXCHANGE UPSTREAM

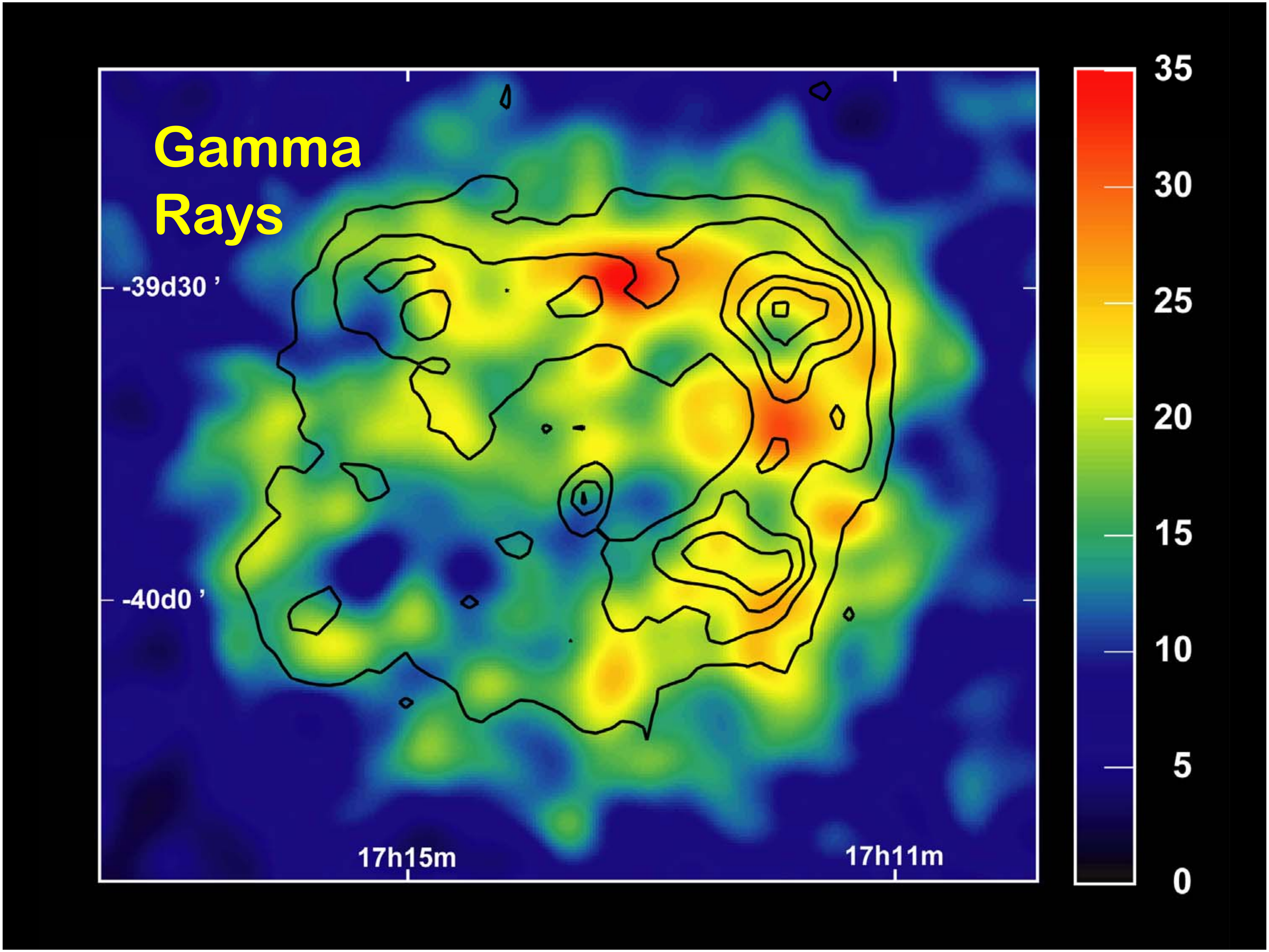
Observation of Balmer dominated shocks:

Possible evidence for a CR precursor in the narrow Balmer line



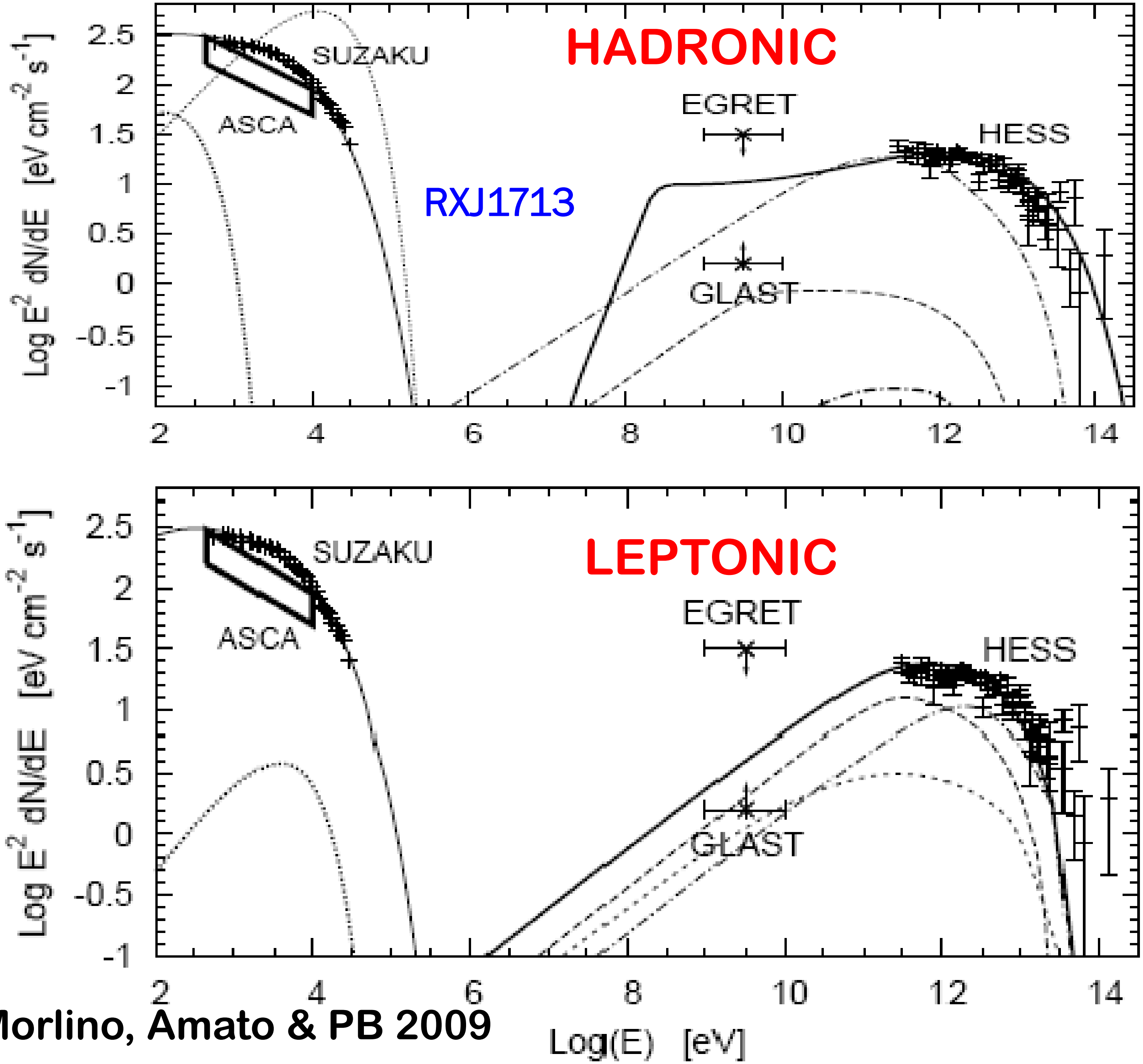
A broadened narrow Hα line from upstream shows that the neutrals and ions have some level of charge exchange → different bulk velocities and/or T's between the two components →

CR precursor



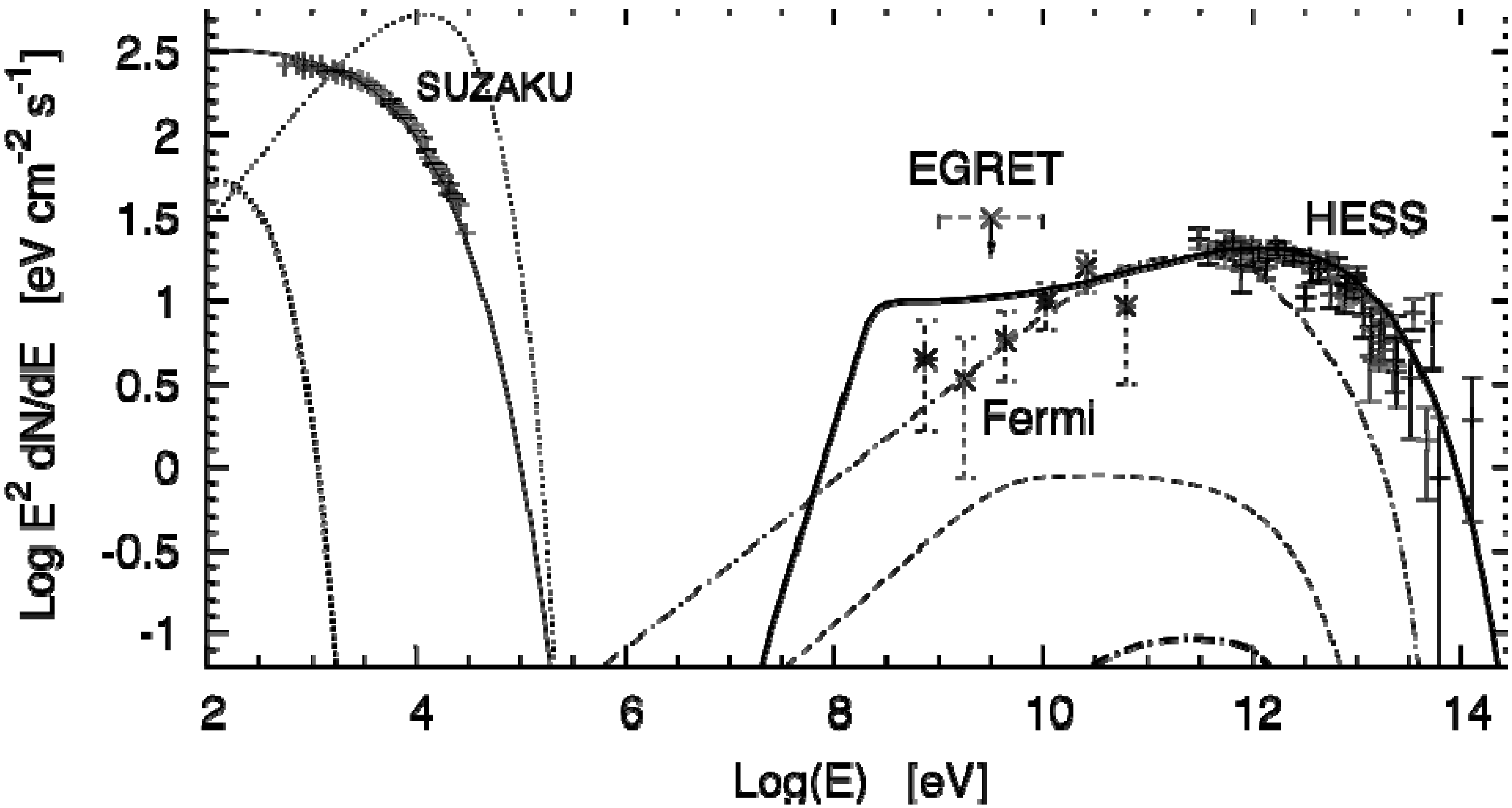
Gamma
Rays
-39d30 '
-40d0 '
17h15m
17h11m
35
30
25
20
15
10
5
0

RXJ1713



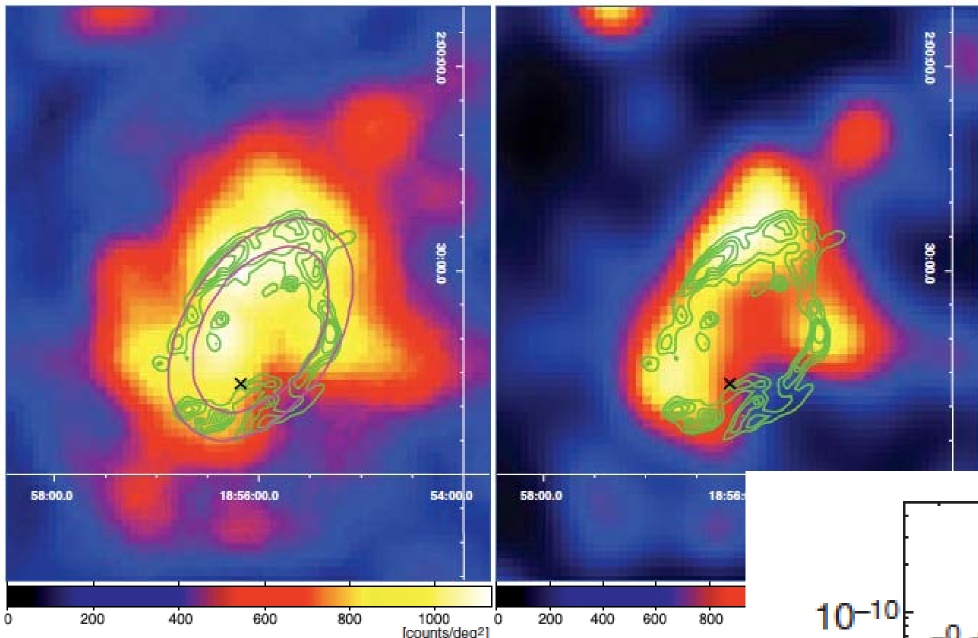
Morlino, Amato & PB 2009

RXJ1713 with Fermi data

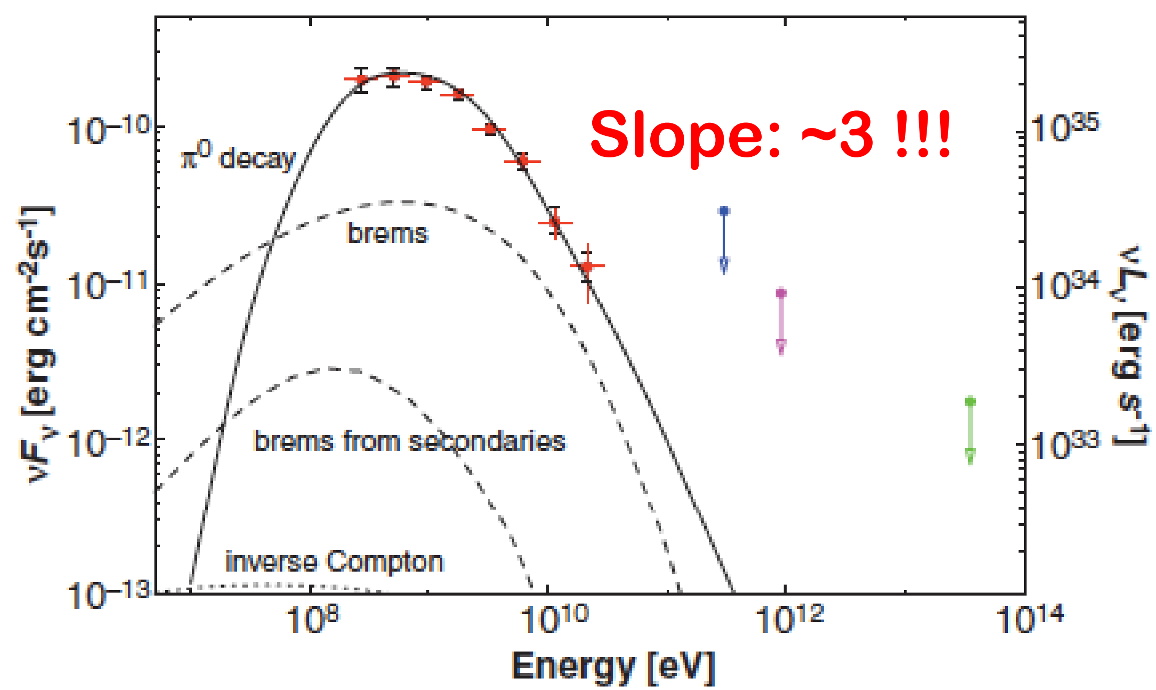


1. e/p Equilibration downstream? (Morlino et al. 2009)
2. Very low value of K_{ep} at given time
3. Lines from non-equilibrium ionization ? (Ellison et al. 2010)
4. What are those Fermi data points telling us?

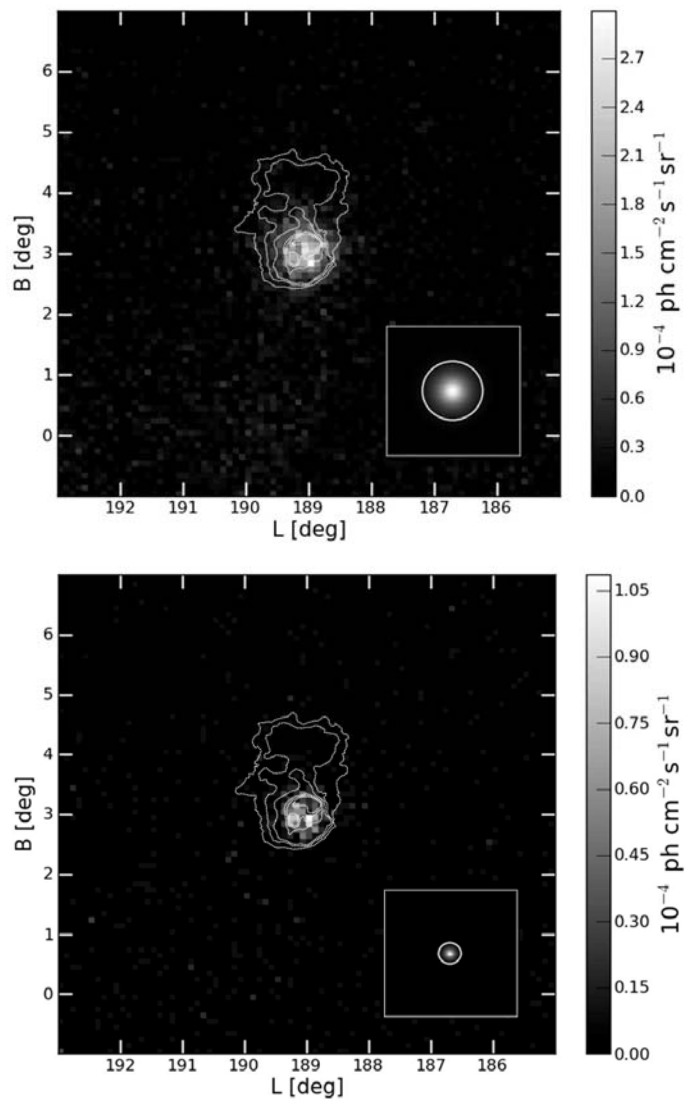
W44 – an old SNR

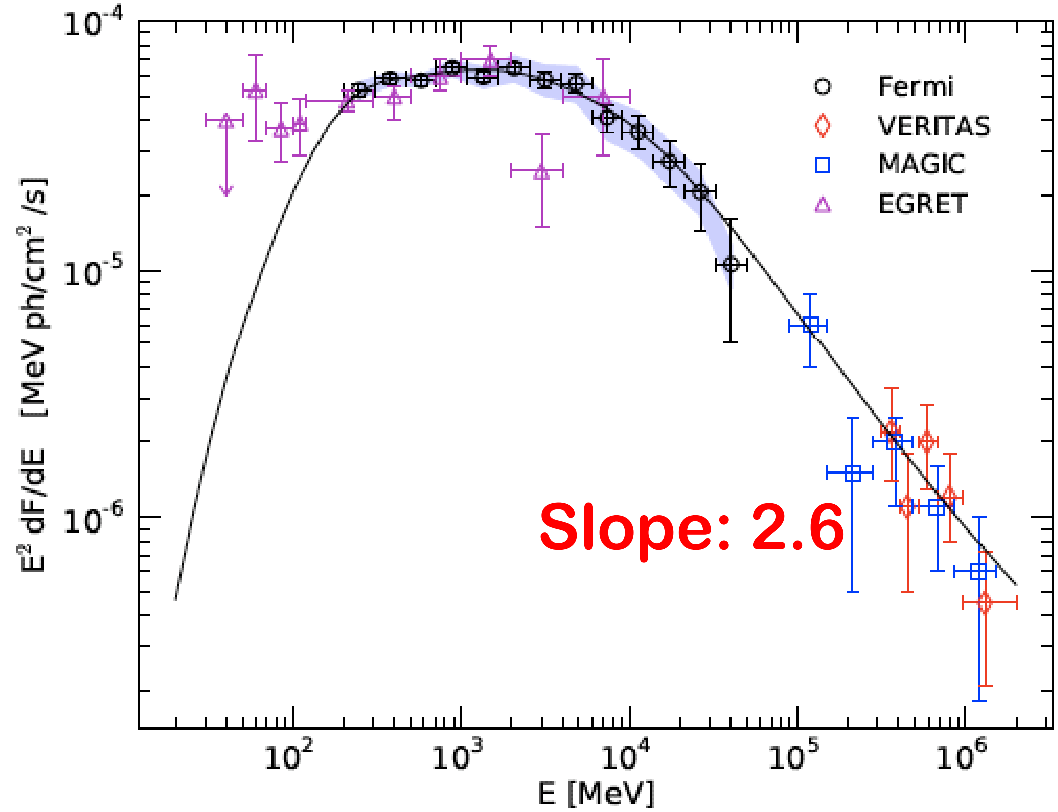


Age: 20kyrs



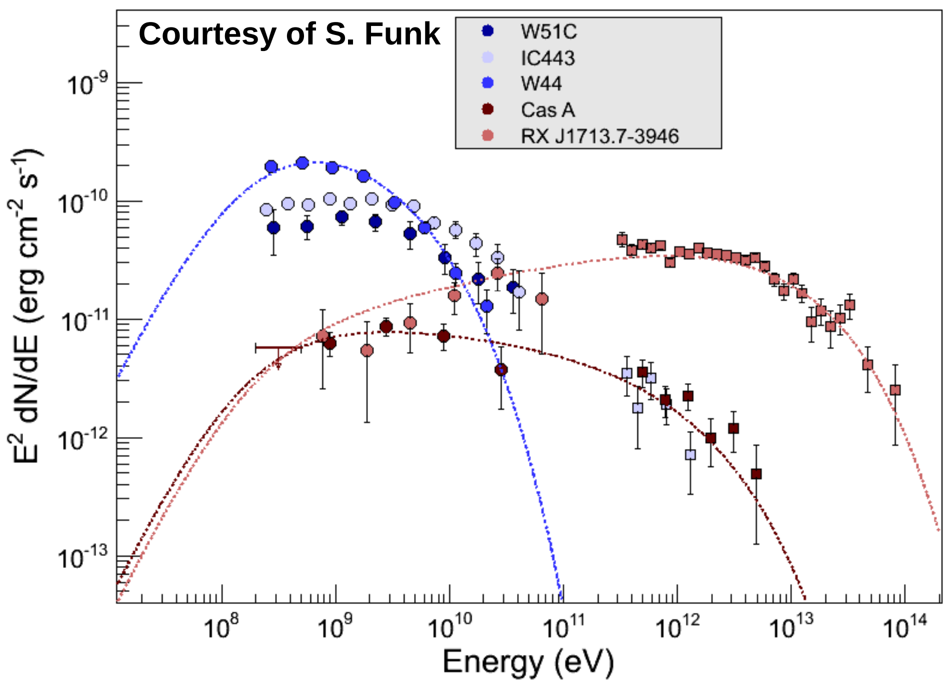
IC443 – possible interaction with a mc





Age very uncertain: 2kyr-30kyr

A Puzzling situation



- Most SNR detected by Fermi have relatively steep spectra (some exceptions, such as RXJ1713)

- The predicted spectra would naively require steep diffusion $D(E) \sim E^{0.7}$ in conflict with anisotropy measurements

A *small print* in the theory of DSA?:
a point as important as poorly known

$$\tilde{u}(x)\frac{\partial f_i(x,p)}{\partial x} = \frac{\partial}{\partial x}\left[D_i(x,p)\frac{\partial f_i(x,p)}{\partial x}\right] + \frac{p}{3}\frac{\mathrm{d}\tilde{u}(x)}{\mathrm{d}x}\frac{\partial f_i(x,p)}{\partial p} + Q_i(x,p)$$

Velocity of scattering centers in the shock frame NOT velocity of the plasma

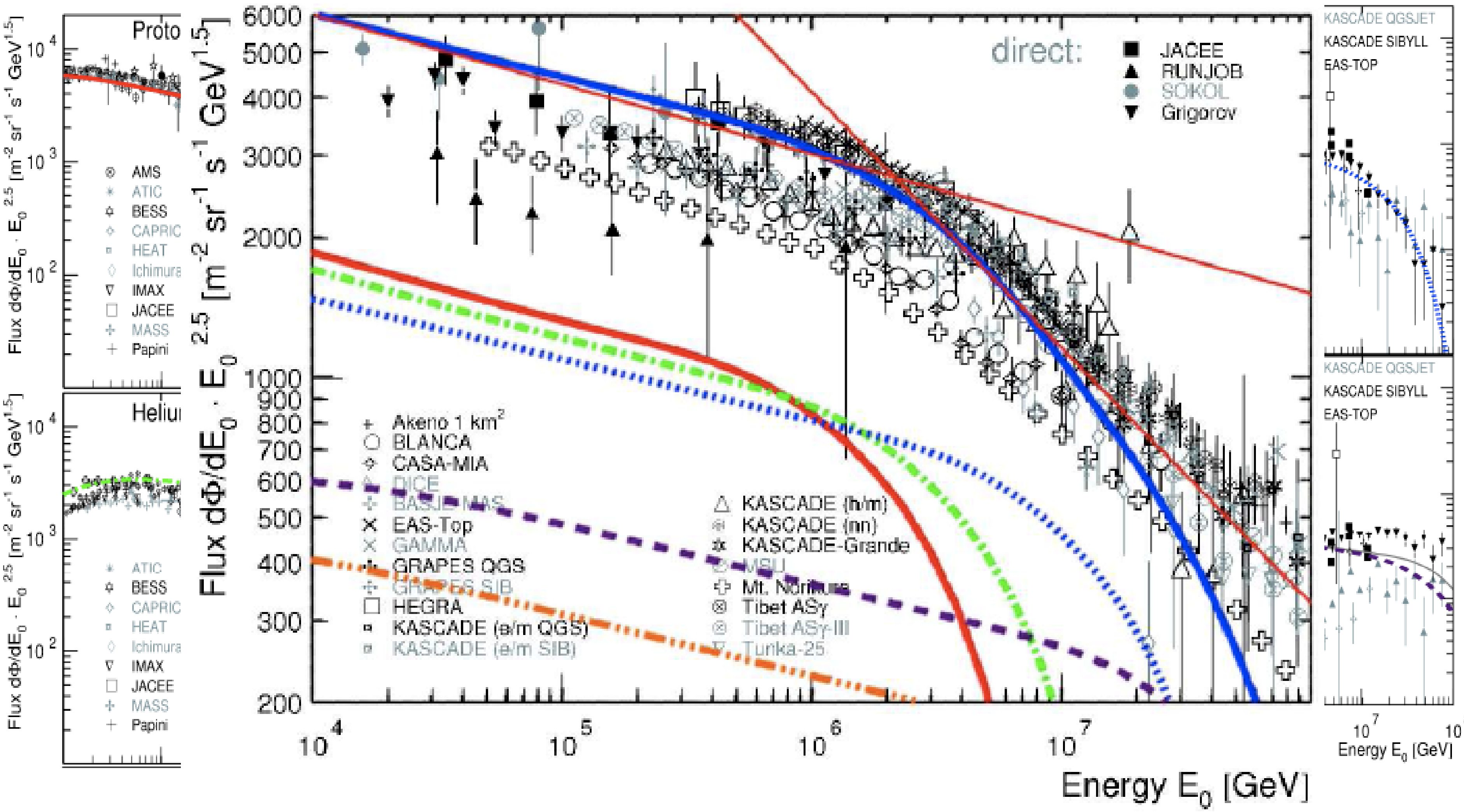
In general the velocity of scattering centers is small and there is no problem

BUT **AMPLIFIED MAGNETIC FIELD → high velocity ???**

$$v_w = \frac{\delta B}{\sqrt{4\pi\rho}} >> v_{A,0}$$

VERY MACROSCOPIC CONSEQUENCES ON SPECTRA!

ROLE OF NUCLEI: The knee

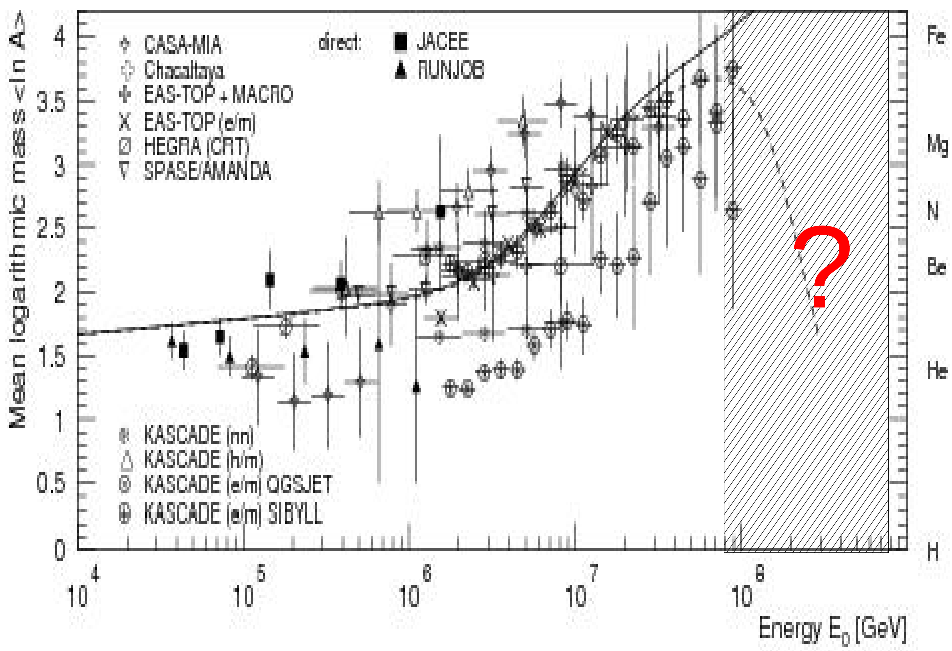


Caprioli, PB, Amato 2010

WHERE DO GALACTIC CR end?

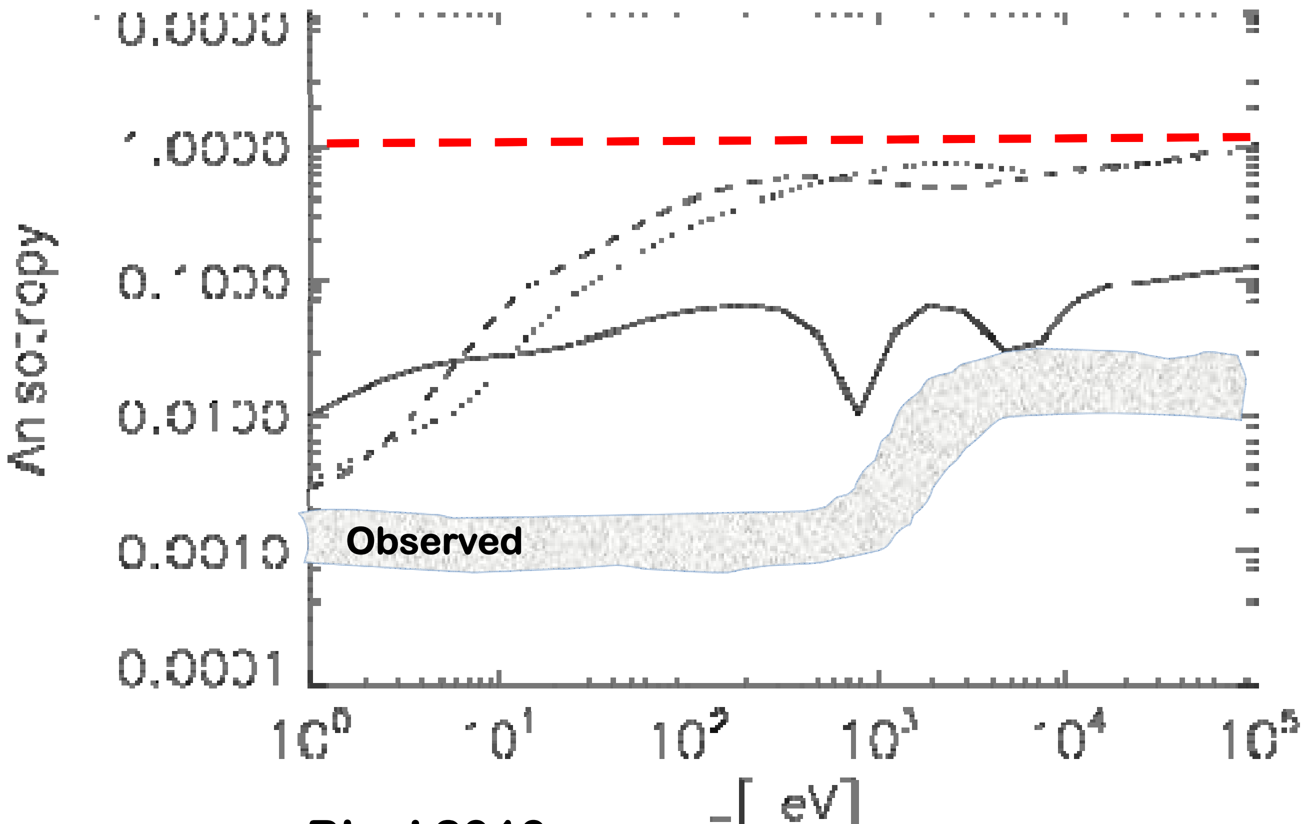
1. The SNR paradigm hints to a galactic CR spectrum ending at ~a few 10^{17} eV

2. Observations of chemical composition also suggest the same trend



Anisotropy of Galactic CR

δ=0.7 Required Efficiency: ~ 50-60%



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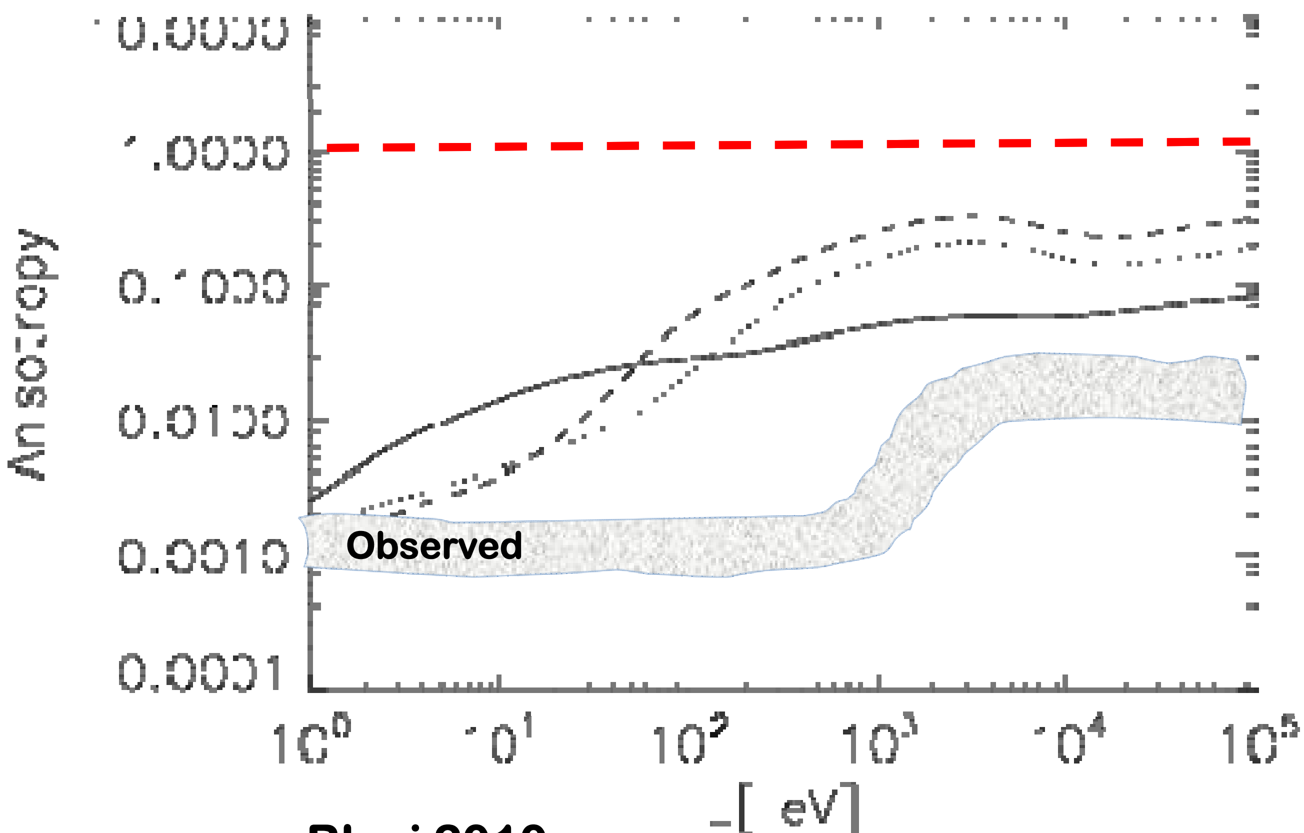
Anisotropy of Galactic CR

δ=0.55 **Required Efficiency: ~ 10-15%**



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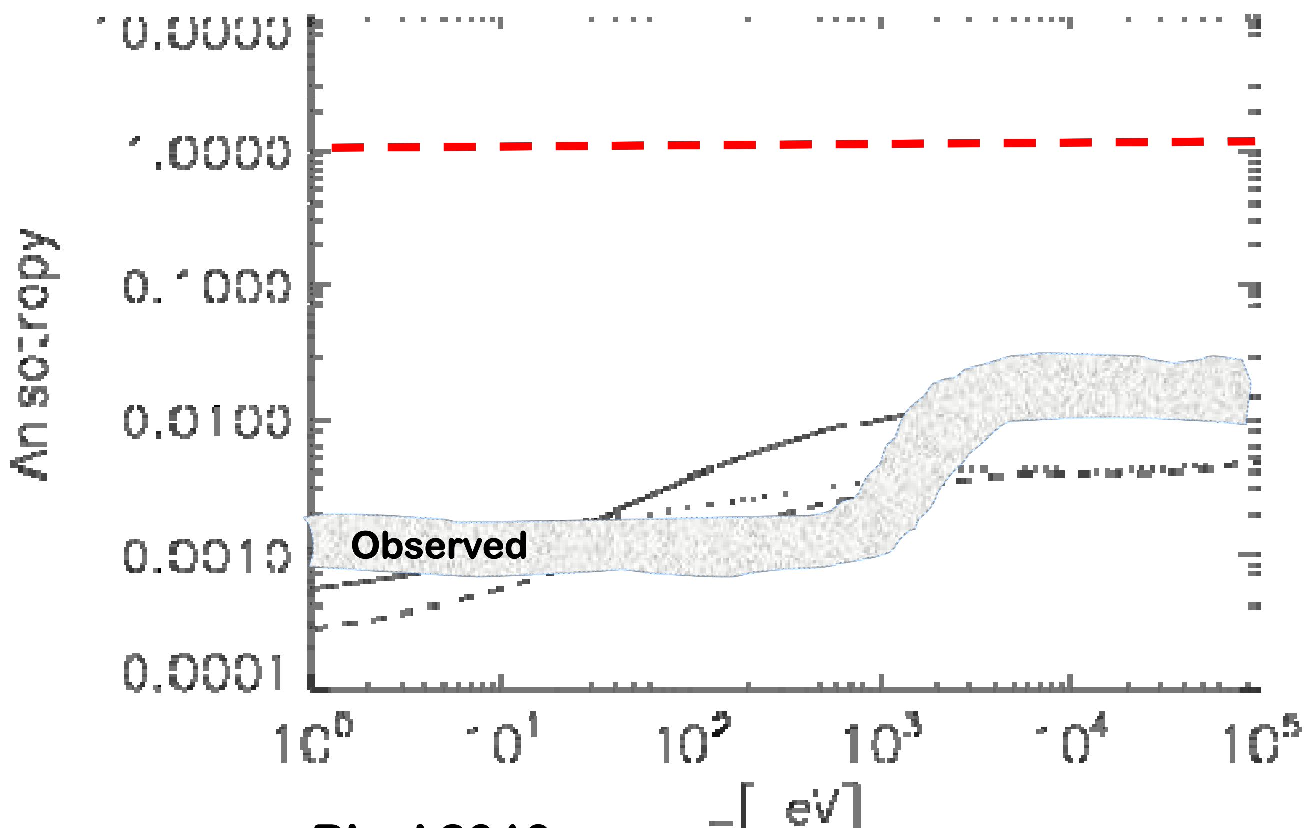
Anisotropy of Galactic CR

δ=1/3   Required Efficiency: ~ 5-10%



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Conclusions

1. Non-linear DSA in (some) SNRs is reliably observed

2. The SNR paradigm collects much circumstantial evidence

3. But some problems remain open

    a. Steep gamma ray spectra
    b. NLDSA predicts flat spectra unless v_W large
    c. Even in this case NLDSA leads to require $\delta=0.55$
    d. Anisotropy still seems problematic

4. Note of caution n. 1: what we see at the Earth is a complex overlap of many factors

5. Note of caution n. 2: SNR of type II, the most frequent, are also the ones which are harder to observe in gamma rays (low density)