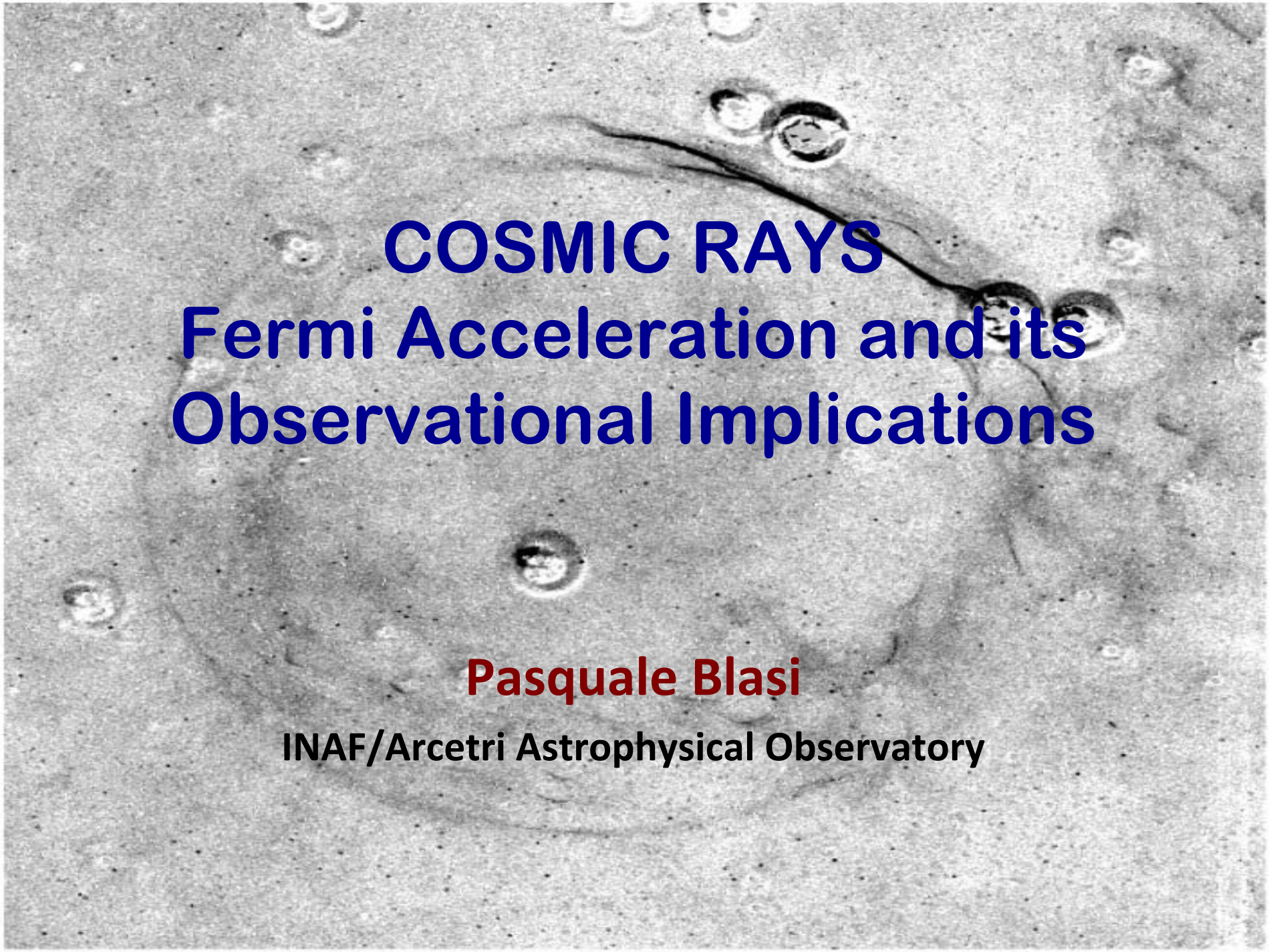


# COSMIC RAYS
# Fermi Acceleration and its Observational Implications

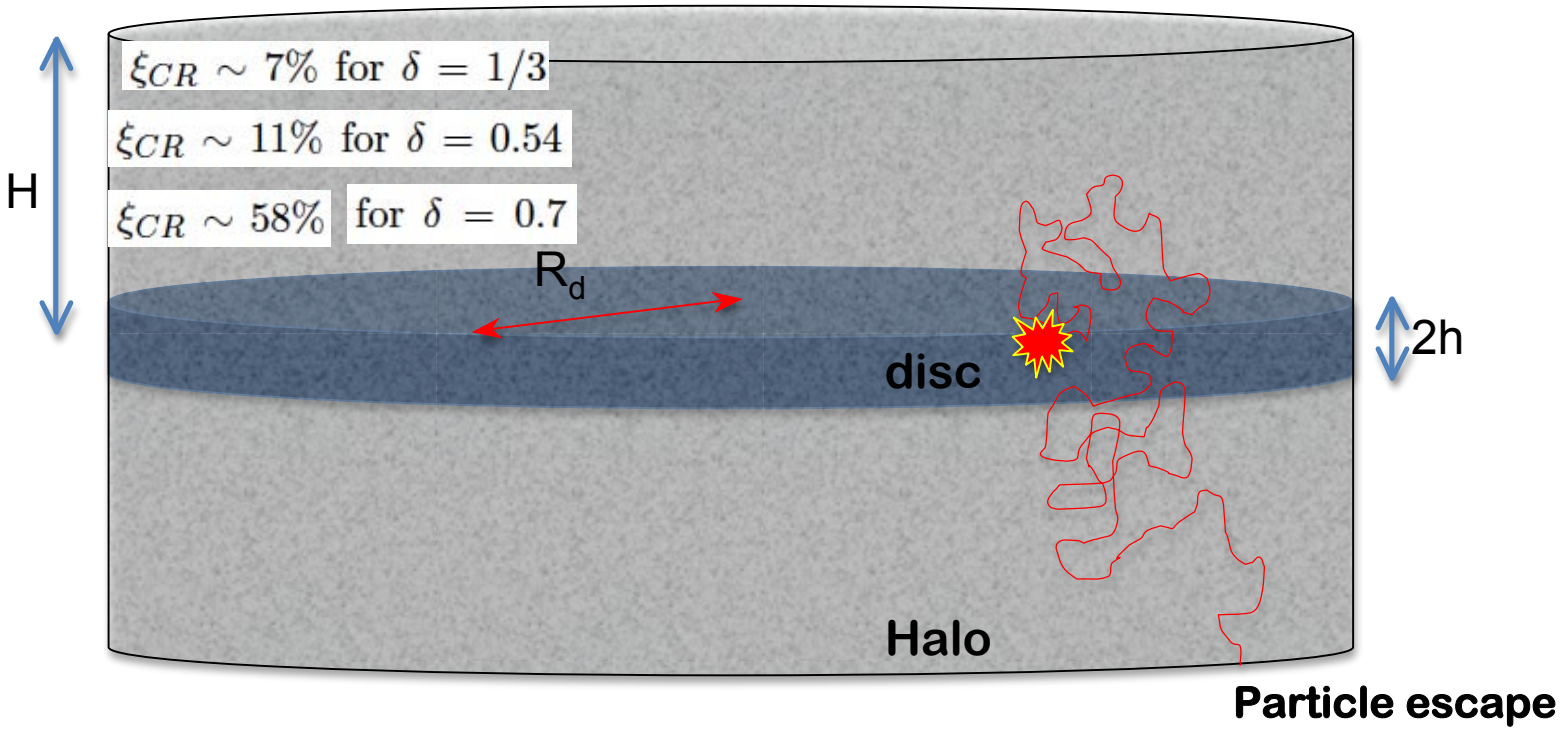
**Pasquale Blasi**

**INAF/Arcetri Astrophysical Observatory**

# WHAT DOES IT MEAN TO SEARCH FOR THE SOURCES OF COSMIC RAYS?

1. SOURCES OF HADRONS
2. …THAT CAN BE PROVEN TO REACH ENERGIES CLOSE TO KNEE
3. WITH A SPECTRUM COMPATIBLE WITH GALACTIC PROPAGATION
4. NO CONFLICT WITH ANISOTROPY
5. SPECTRA OF PROPAGATED NUCLEI COMPATIBLE WITH DATA
6. …THAT SATISFY MULTIFREQUENCY CONSTRAINTS

# Pillars of the SNR paradigm

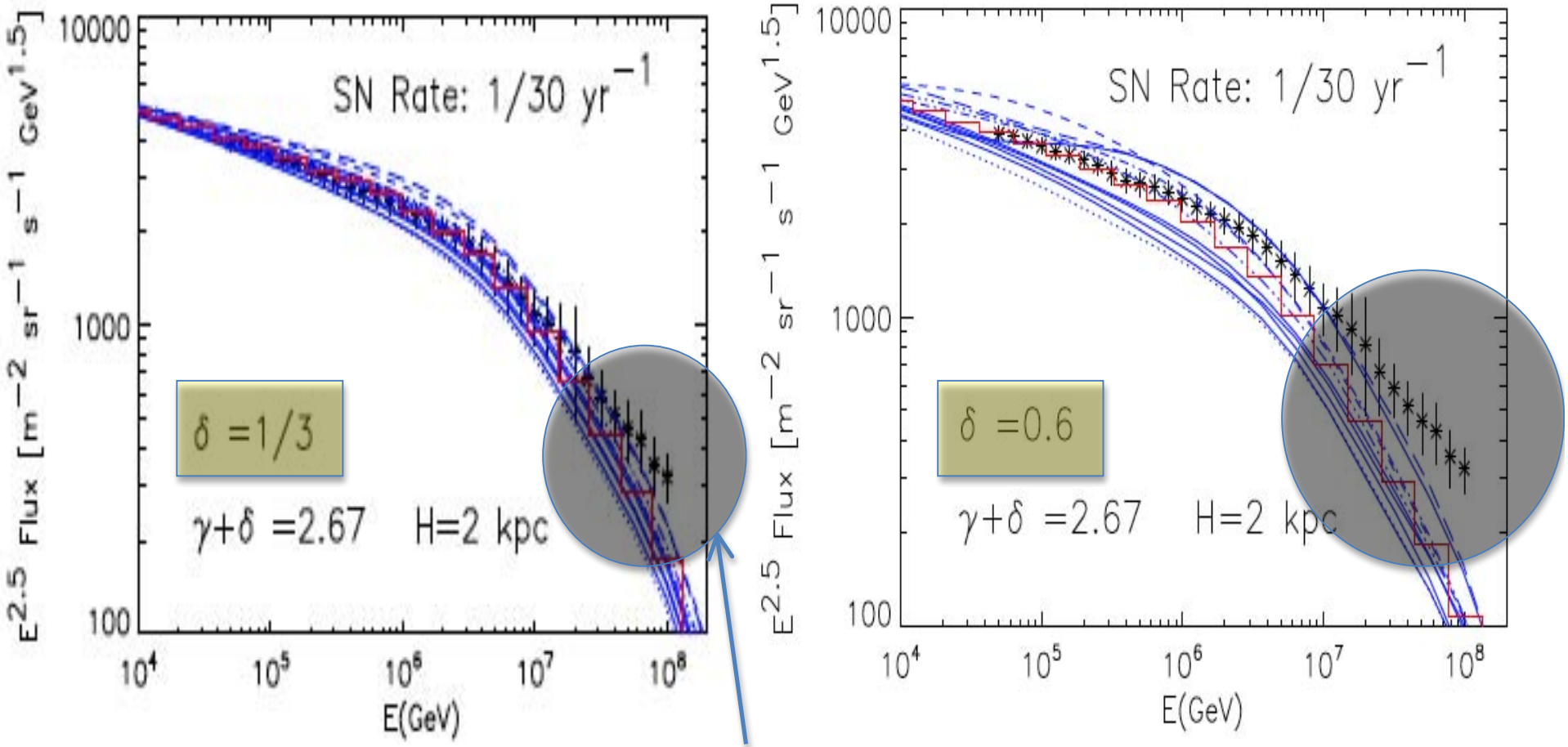



**CRs IN SNR → DIFFUSIVE SHOCK ACCELERATION, $Q(E) \sim E^{-\gamma}$**

**PROPAGATION OF CRs IN THE GALAXY with $D(E) \sim E^{\delta}$ → $n(E) \sim E^{-\gamma-\delta}$**

# CR spectra and SNRs

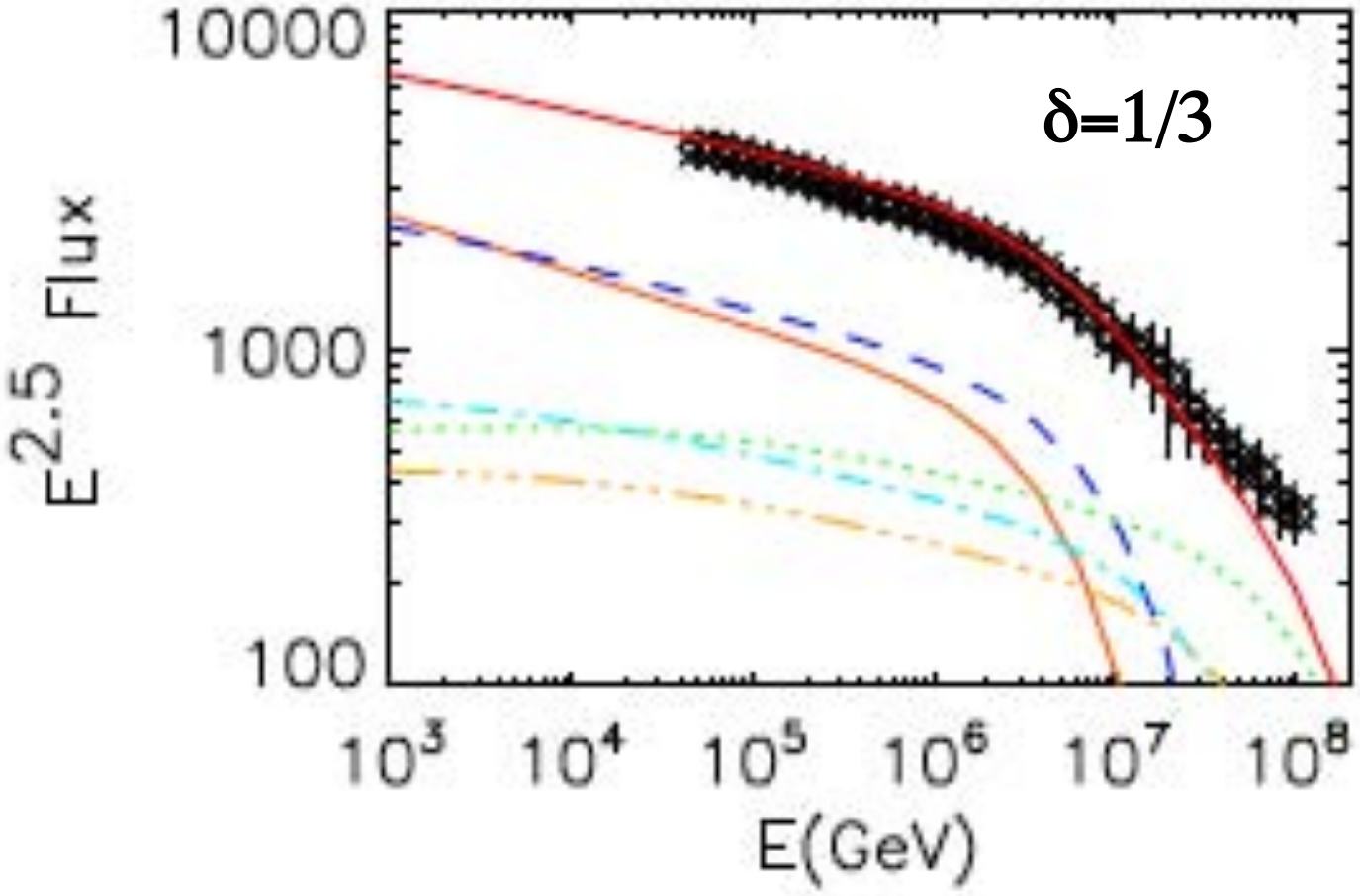
**Blasi & Amato 2011**




Deficit compensated
by extragalactic CRs

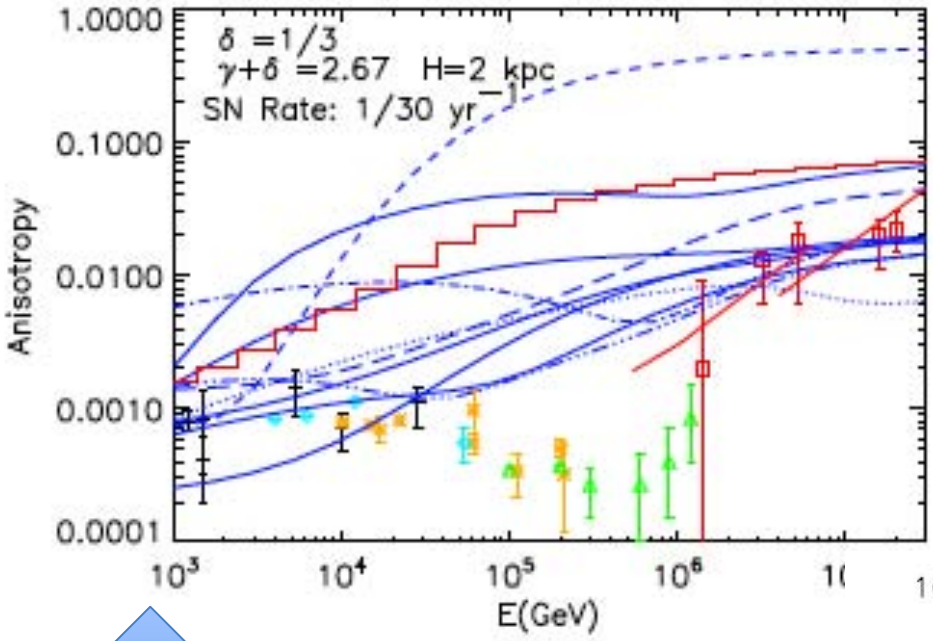
# Chemicals and the KNEE

Blasi & Amato 2011




**ONLY FOR δ=1/3 SPECTRUM OF He HARDER THAN SPECTRUM OF PROTONS AS A RESULT OF SPALLATION**

# CR Anisotropy



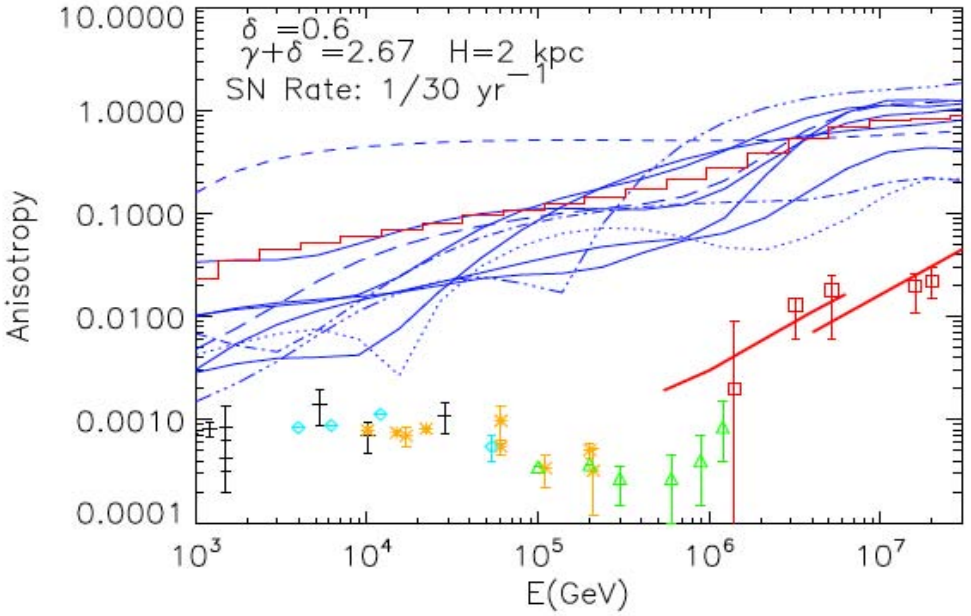

**Naïve expectation:**

$$\delta_A = \frac{3}{2^{3/2}} \frac{1}{\pi^{1/2}} \frac{D(E)}{Hc}$$

**proportional to $E^{\delta}$**

δ=1/3

δ=0.6




**Blasi & Amato 2011**

# THEORY OF CR ACCELERATION IN SNRs

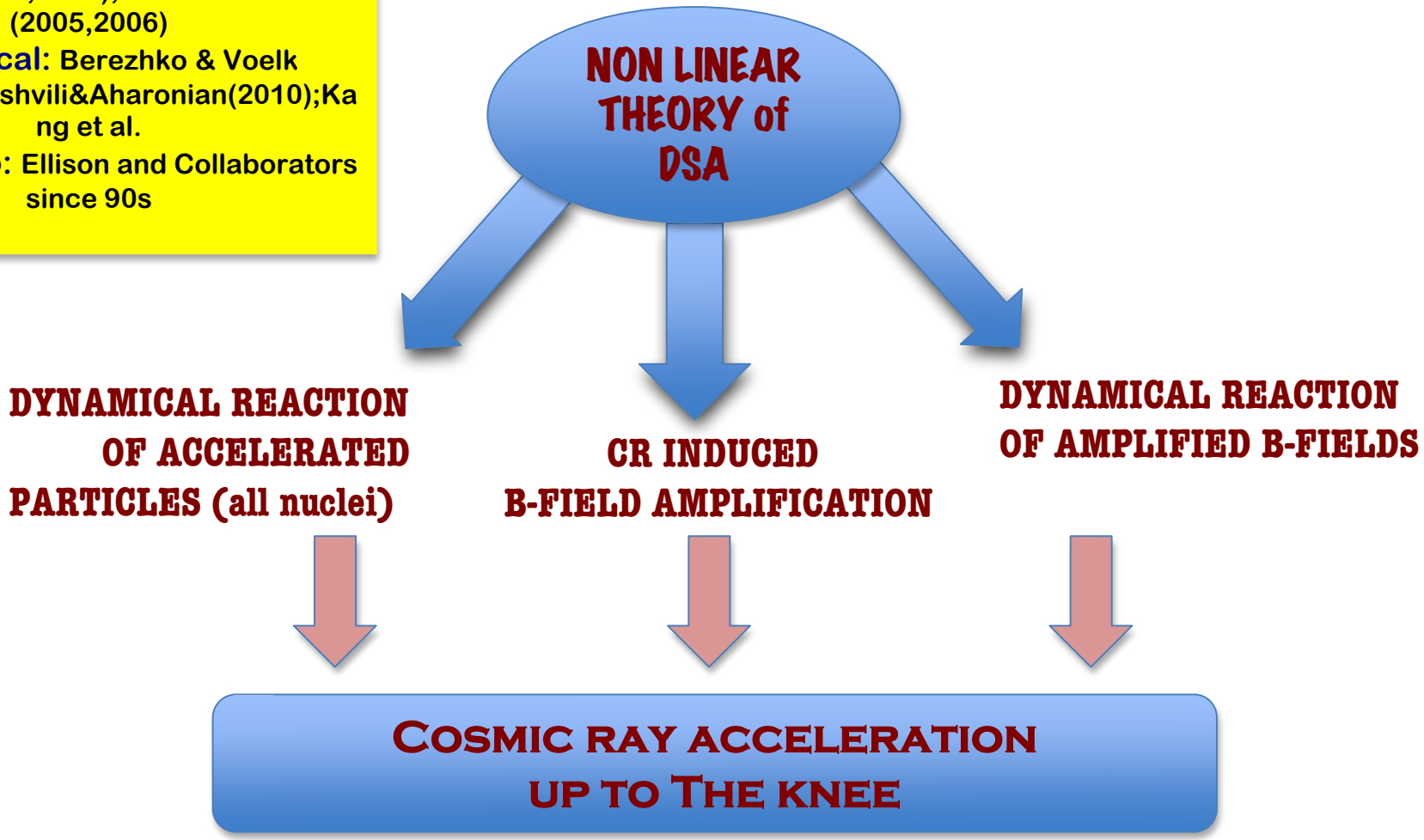
## Diffusive Shock Acceleration

# Particle acceleration in SNRs requires a non linear theory

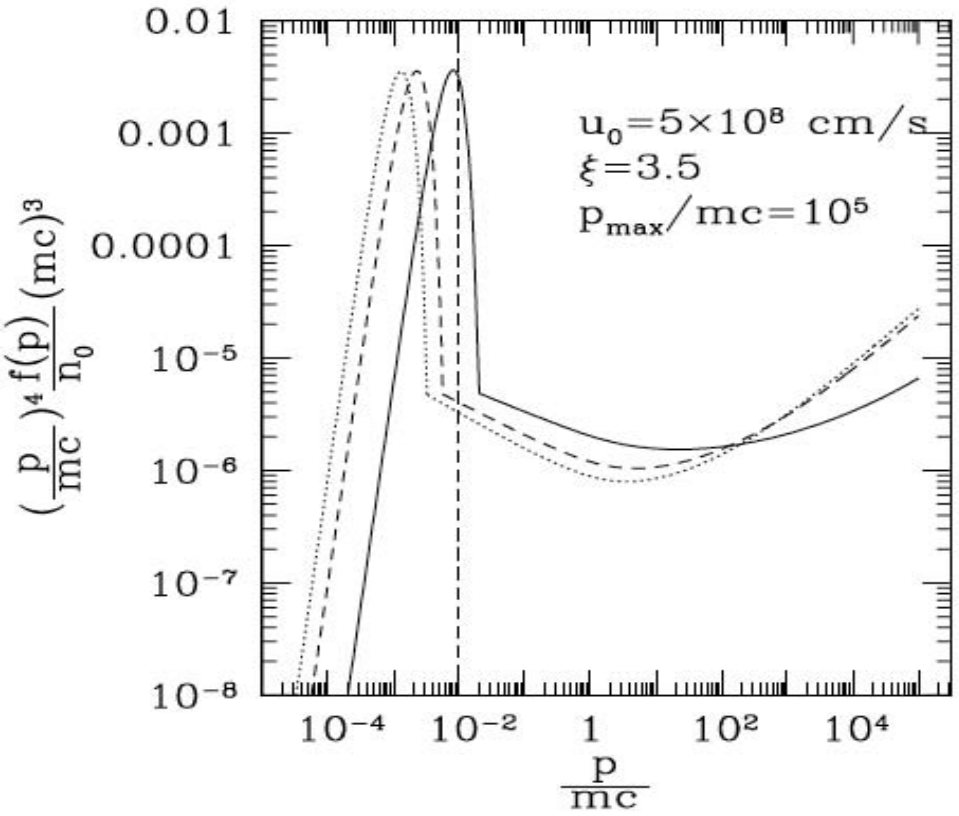
**Analytical:** Malkov(1997,1999), Blasi(2002,2004),Amato&Blasi (2005,2006)

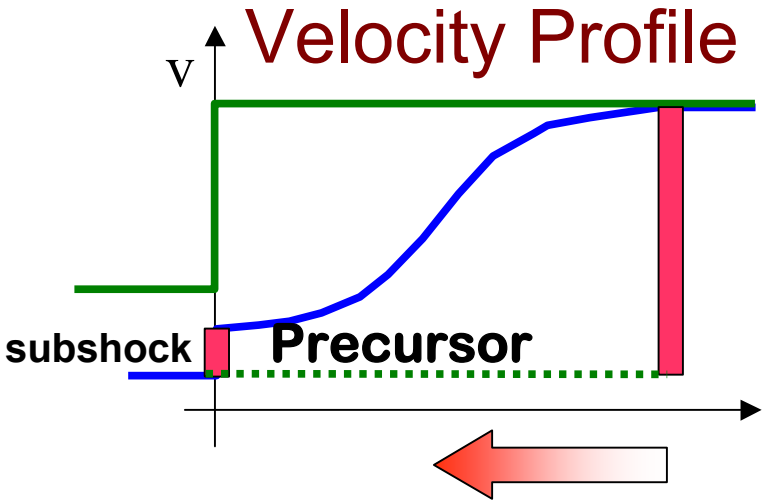
**Numerical:** Berezhko & Voelk (1997),Zirakashvili&Aharonian(2010);Kang et al.

**MonteCarlo:** Ellison and Collaborators since 90s



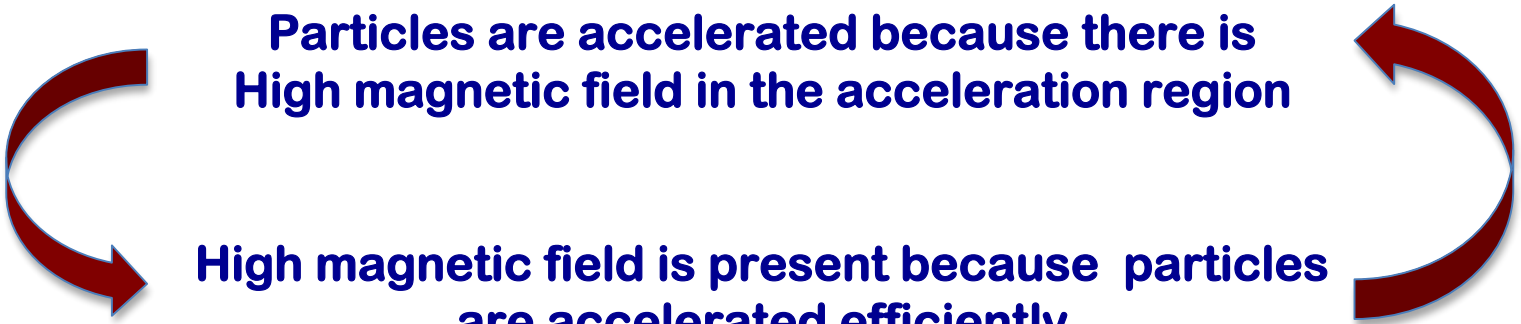
# Dynamical Reaction of Accelerated Particles



# MAGNETIC FIELD AMPLIFICATION

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




**Without this non-linear process, no acceleration of CR to High energies (and especially not to the knee!)**

**BUT…**

## …MAGNETIC FIELD CAN BE AMPLIFIED BY

1.RESONANT STREAMING (Bell 78, Achterberg 83, Zweibel 78)

Fast generation, fast scattering … saturation?

2. NON RESONANT STREAMING (Bell 04, Amato & PB 09)

Probably more efficient generation rate but inefficient scattering

3. SHOCK CORRUGATION (DOWNSTREAM) Giacalone & Jokipii 07

Not CR induced!
It happens downstream only, it does not help with particle acceleration unless perpendicular shock

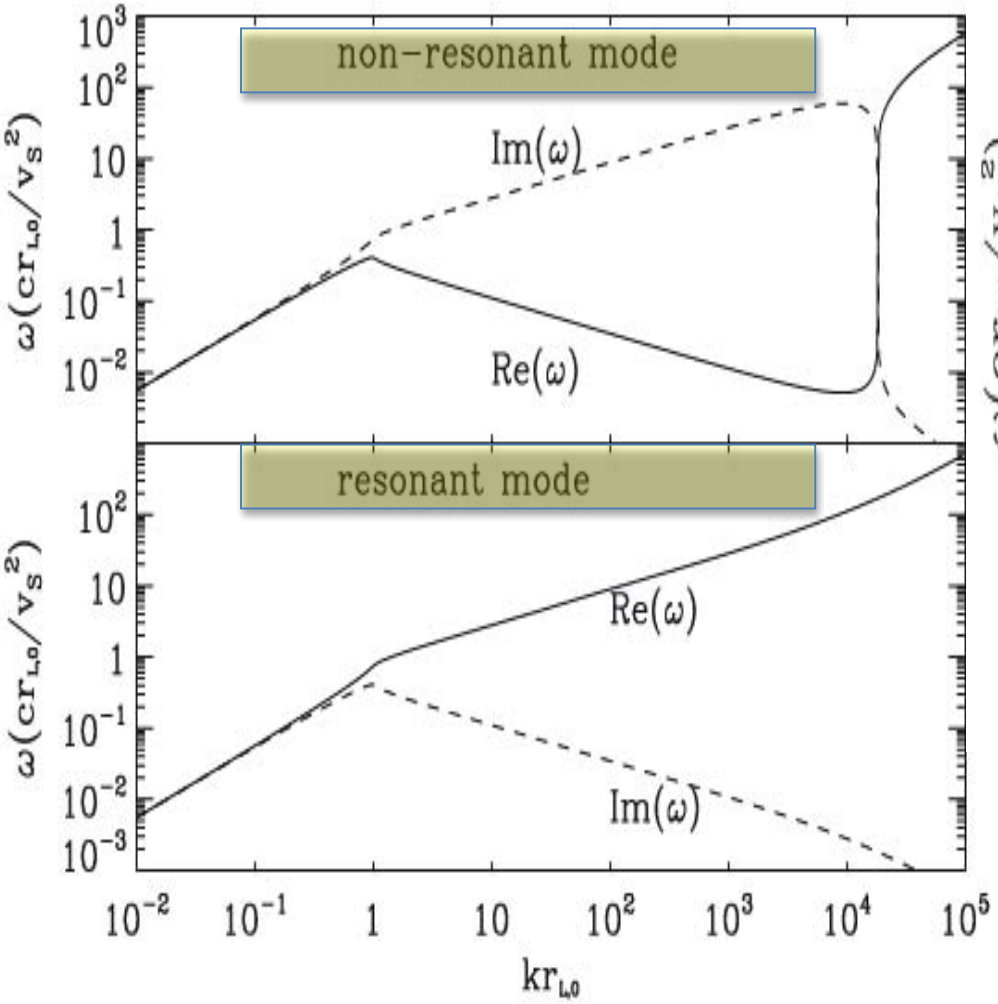
4. VORTICITY IN THE PRECURSOR (PB, Matthaeus, et al. 11)

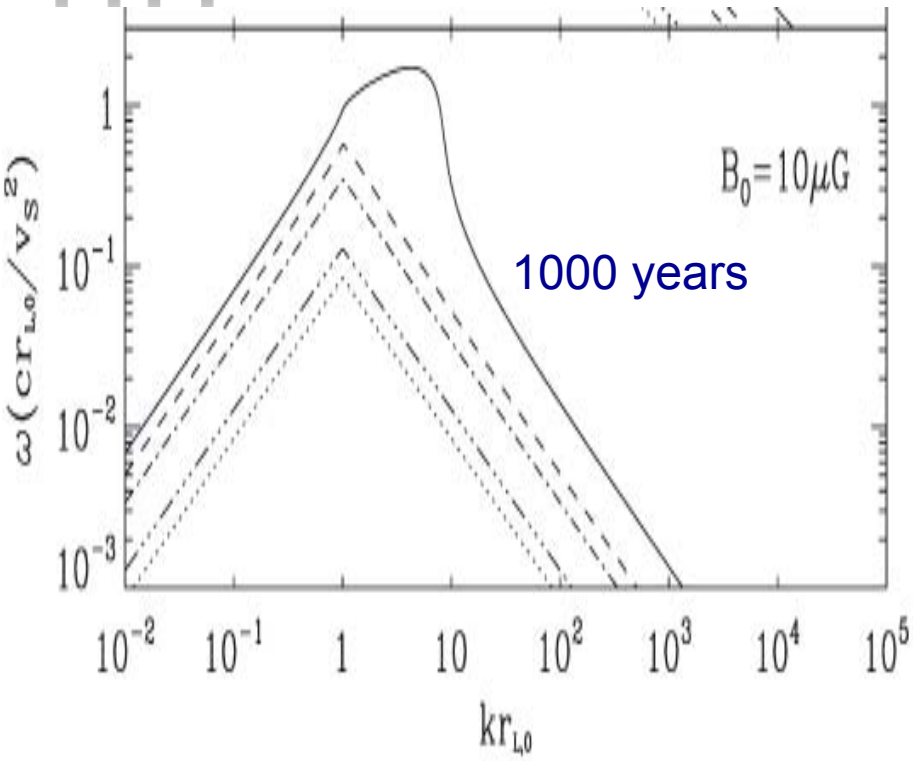
Potentially very interesting, power on large scales

5. FIREHOSE INSTABILITY (Shapiro et al. 98)

Potentially very interesting, power on large scales

# GROWING MODES in CR STREAMING INSTABILITY




**Amato & PB 2009, Bell 2004**

# 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 $\delta B/B \sim 1$ 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)

# Successes of the SNR paradigm

## *Observation of X-ray rims*

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

**The synchrotron limited thickness is:**

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

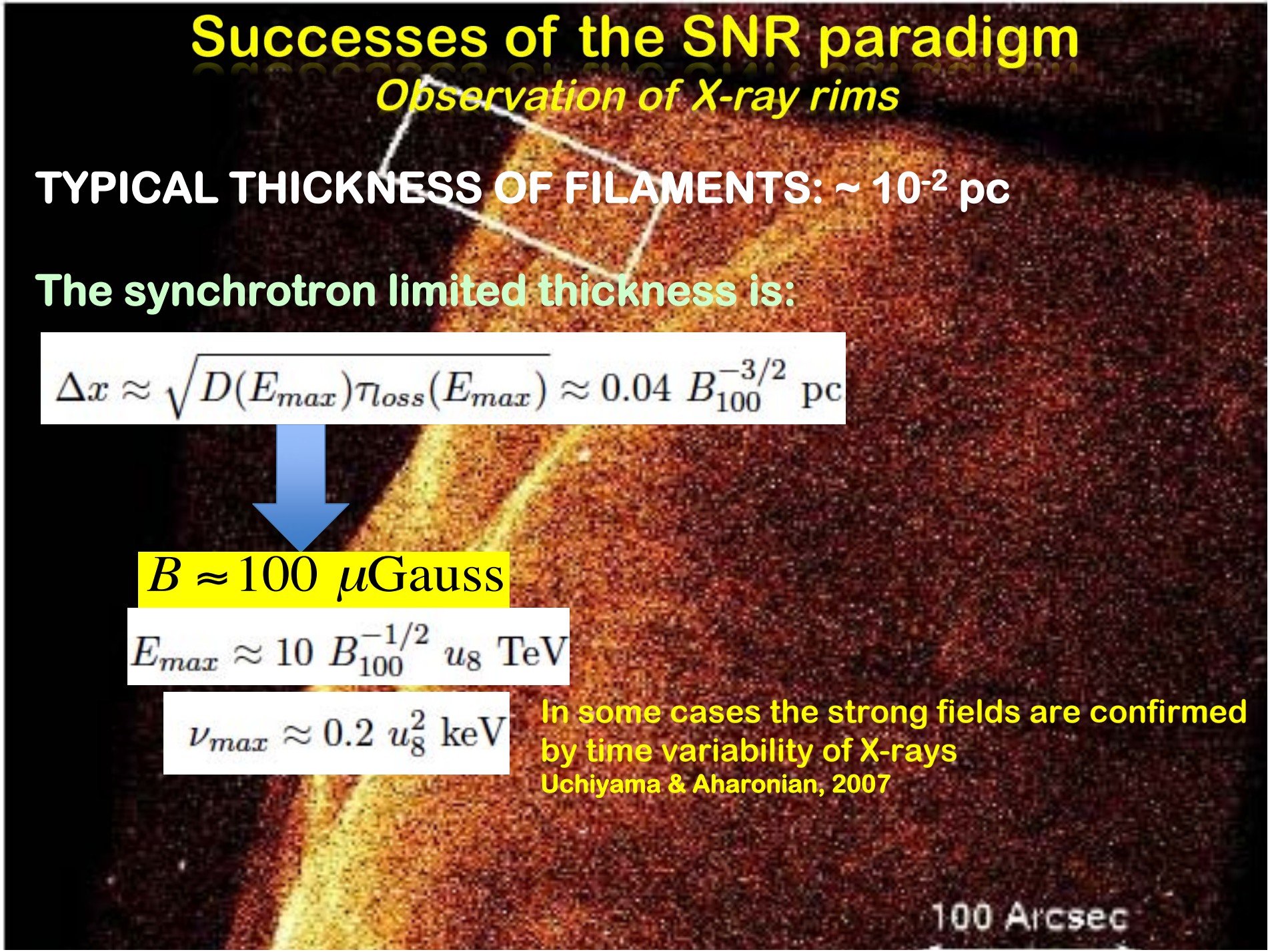
$$B \approx 100\ \mu\mathrm{Gauss}$$

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

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

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

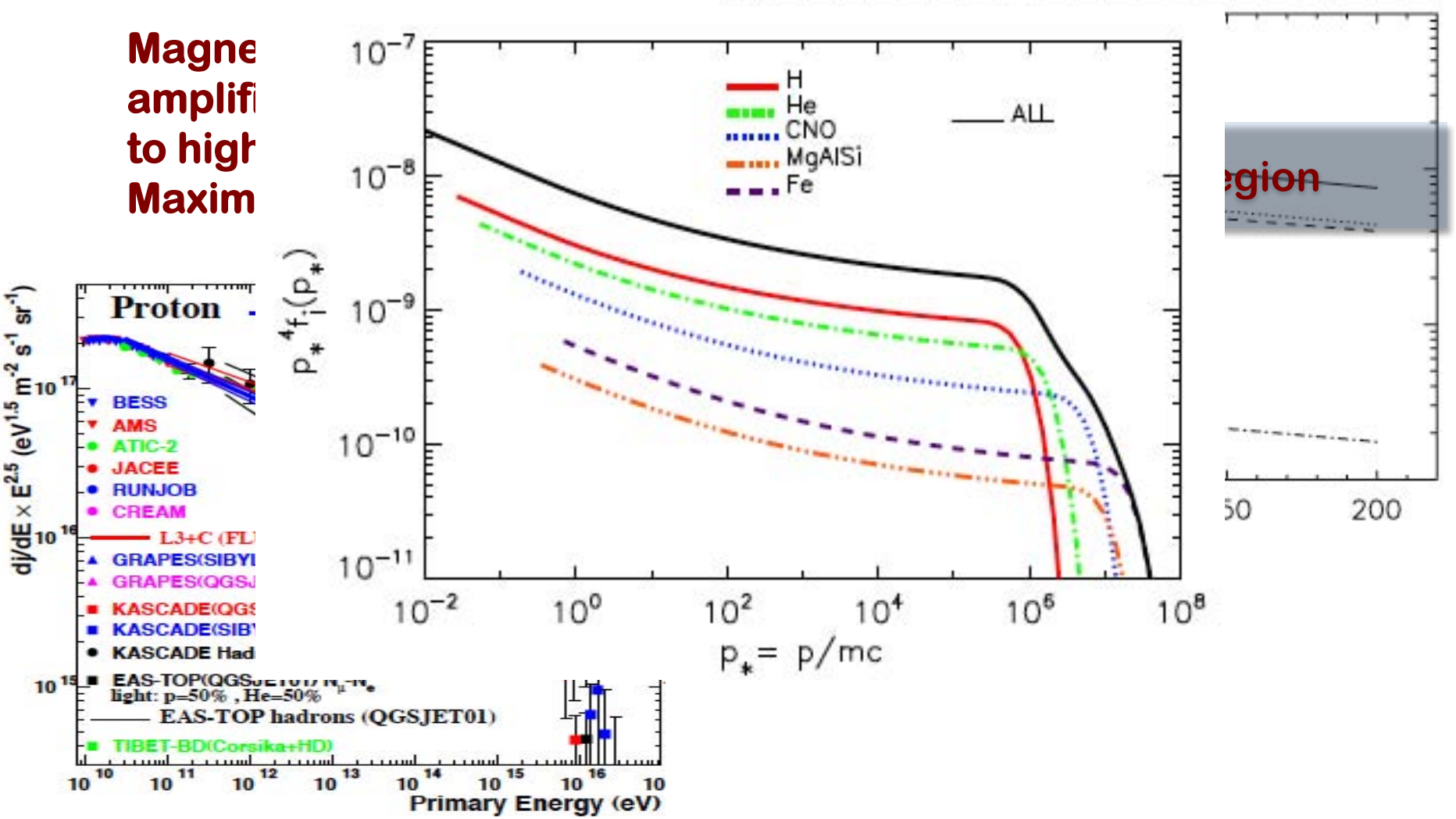
Uchiyama & Aharonian, 2007



# Successes of the SNR paradigm

## *Max energy and the knee*

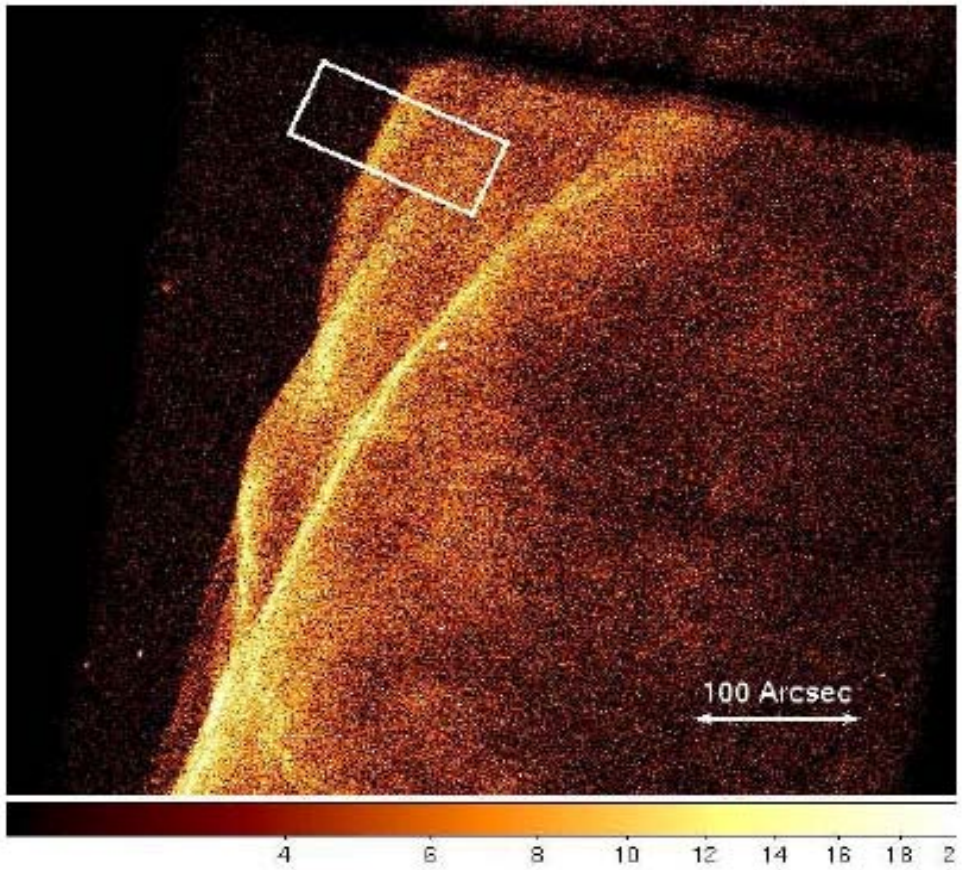
**Magne**
**amplif**
**to high**
**Maxim**



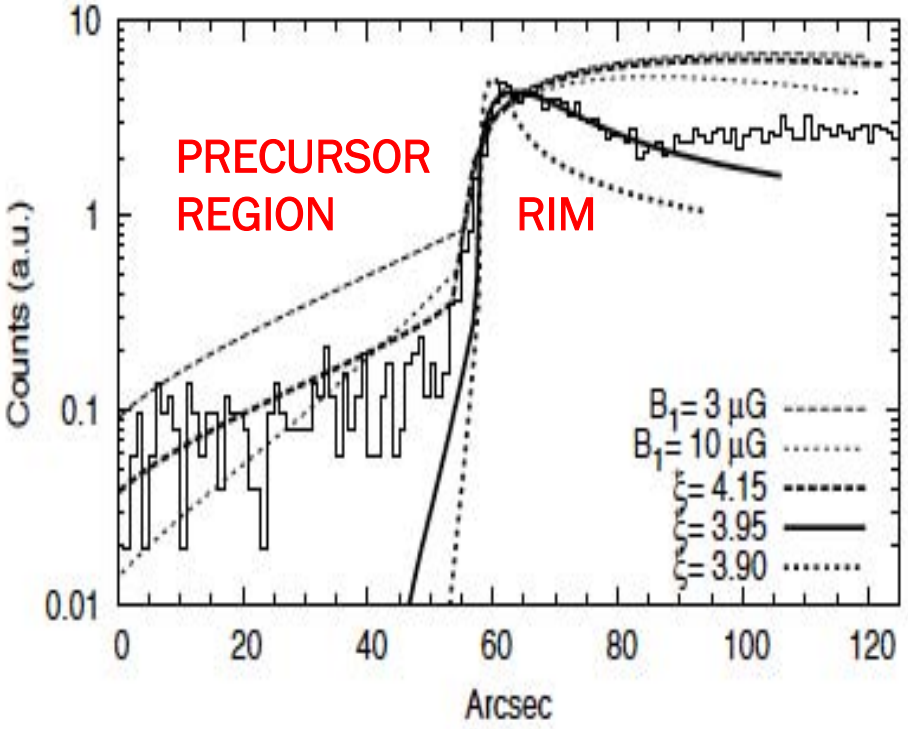

Data from Bertaina et al. 2008

# Successes of the SNR paradigm

## *Evidence for a CR precursor ?*




| $\xi$ | $B_1$ ($\mu$G) | $B_2$ ($\mu$G) | $R_{sub}$ | $R_{tot}$ |
|---|---|---|---|---|
| 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 |
| $\infty$ | 3.0 | 10 | 4.00 | 4.00 |
| $\infty$ | 10 | 33 | 4.00 | 4.00 |




Morlino, Amato, PB & Caprioli 2010

**Ambiguity with perpendicular field**

# ROLE OF GAMMA RAY OBSERVATIONS

## EFFICIENT CR ACCELERATION ≠ HADRONIC GAMMAS

IN SN II → EXPLOSION IN BUBBLE → SMALL TARGET DENSITY (~$10^{-3}$cm$^{-3}$)

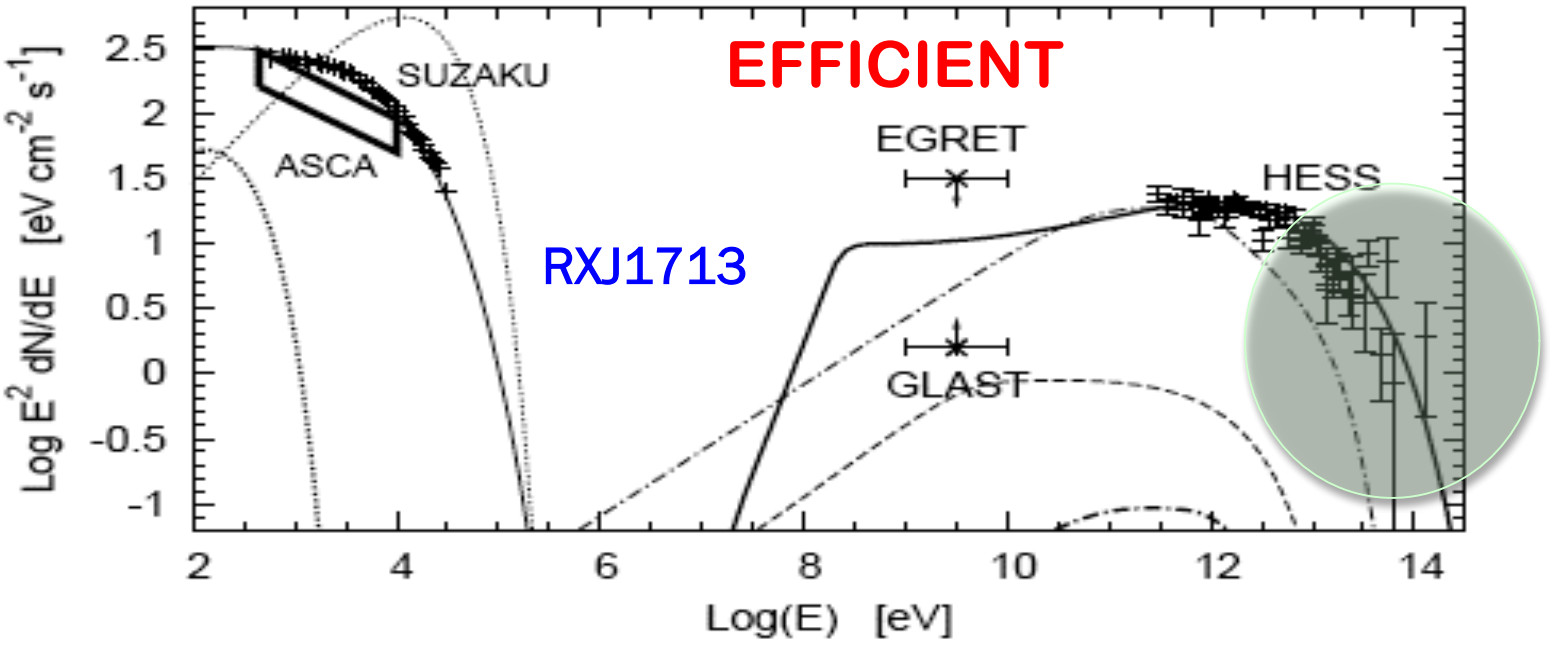
EFFICIENCY IS TIME DEPENDENT

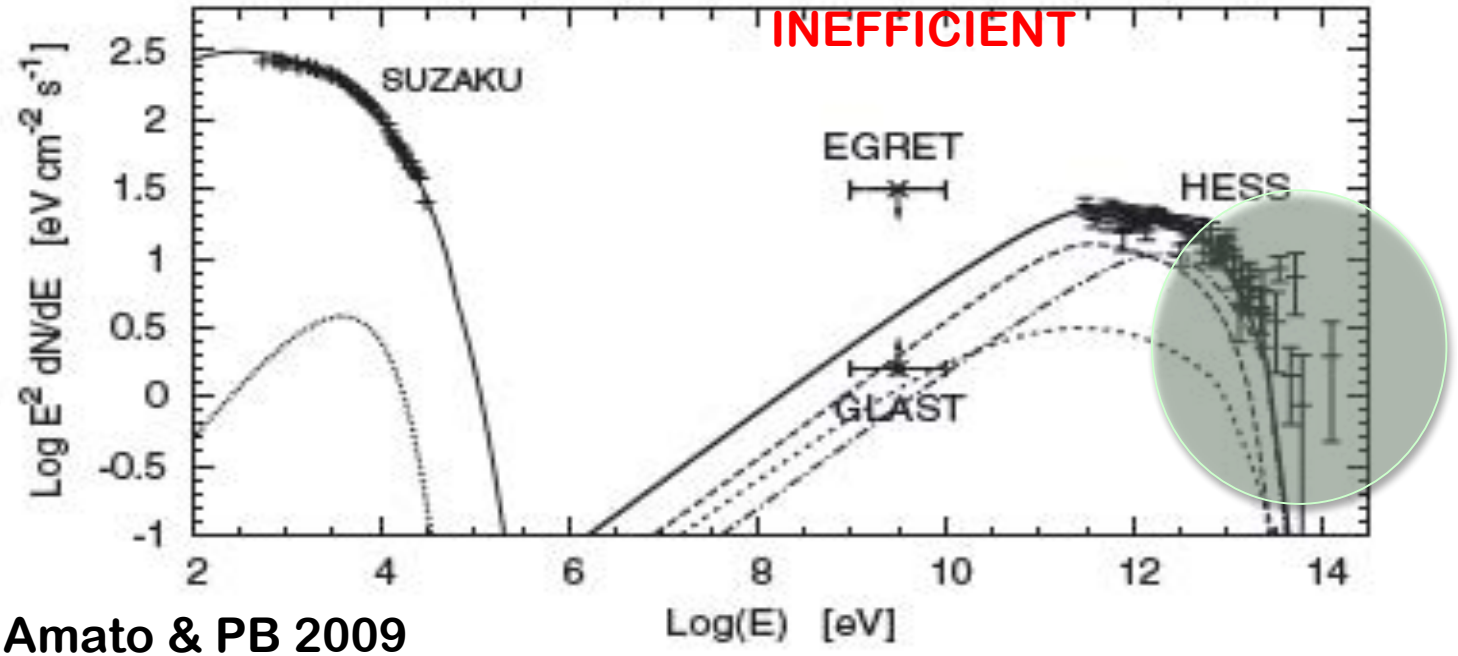
MAX ENERGY IS TIME DEPENDENT → HARD TO CATCH A PEVATRON

YOU COULD SEE GAMMAS FROM MC NEAR SNR, BUT PROBLEMATIC INTERPRETATION (SEE BELOW)

(PROBABLY MC MORE USEFUL TO INVESTIGATE THE PROBLEM OF ESCAPE)

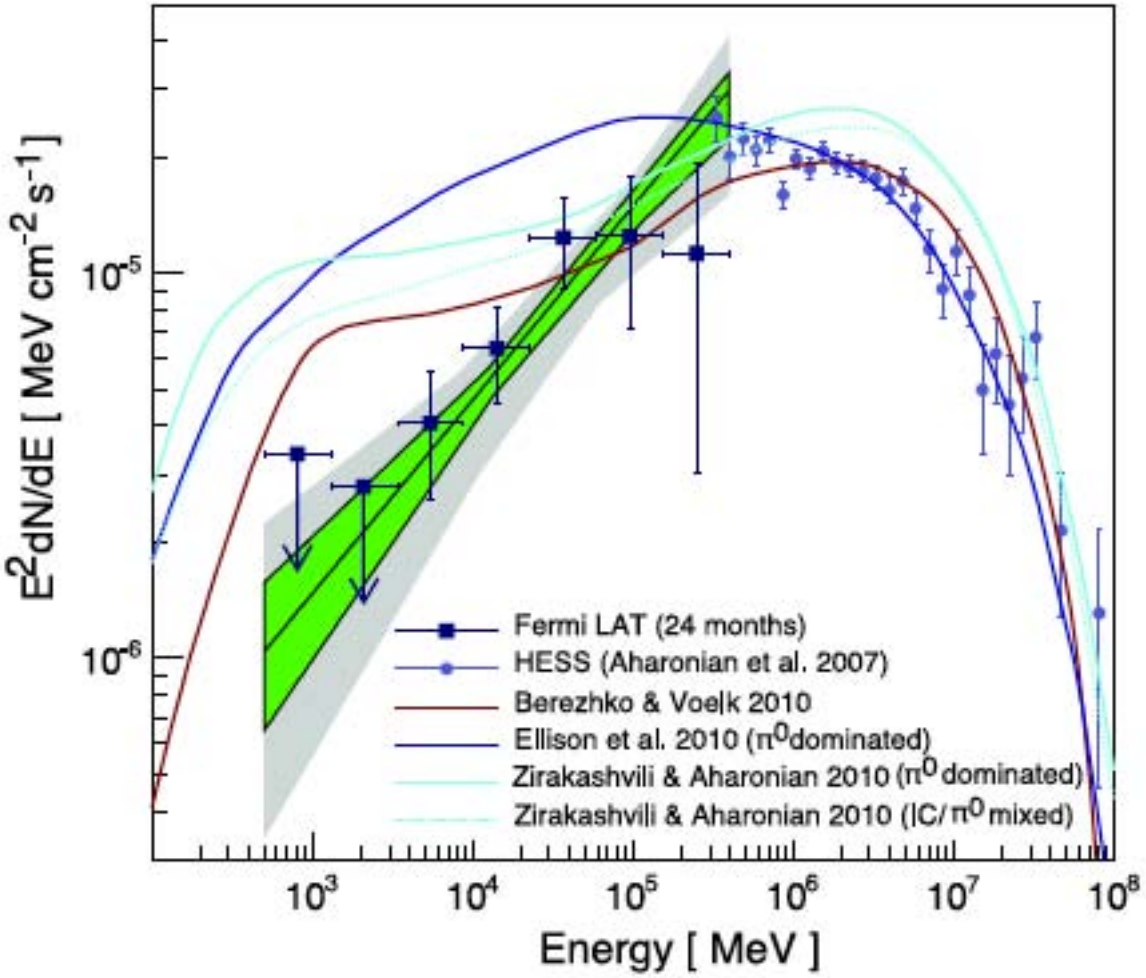
RXJ1713




**Morlino, Amato & PB 2009**

# The power of wide E range




Fermi Coll. 2011

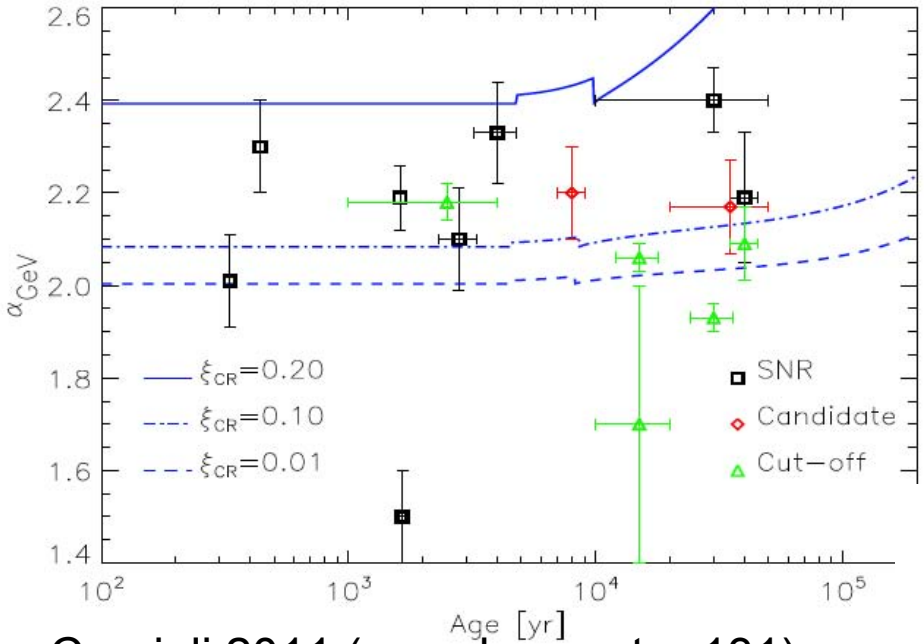
SOME OPEN QUESTIONS:

1.Photon background?

2.Thickness of filaments?

3.KN regime

# TROUBLE WITH SLOPES ?

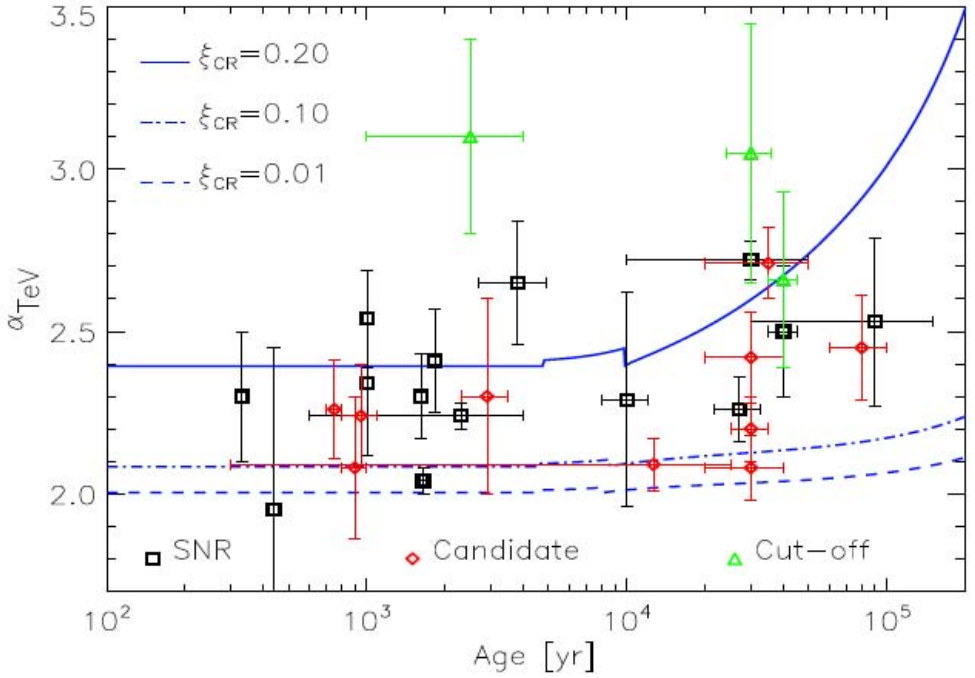



Caprioli 2011 (see also poster 131)

**VERY SURPRISING TO SEE THAT THE REQUIRED ACCELERATION EFFIC ARE HIGH BUT THE SPECTRA ARE STEEP**

**POSSIBLE SIGNATURE OF FINITE SPEED OF THE SCATTERING CENTERS !!!???**

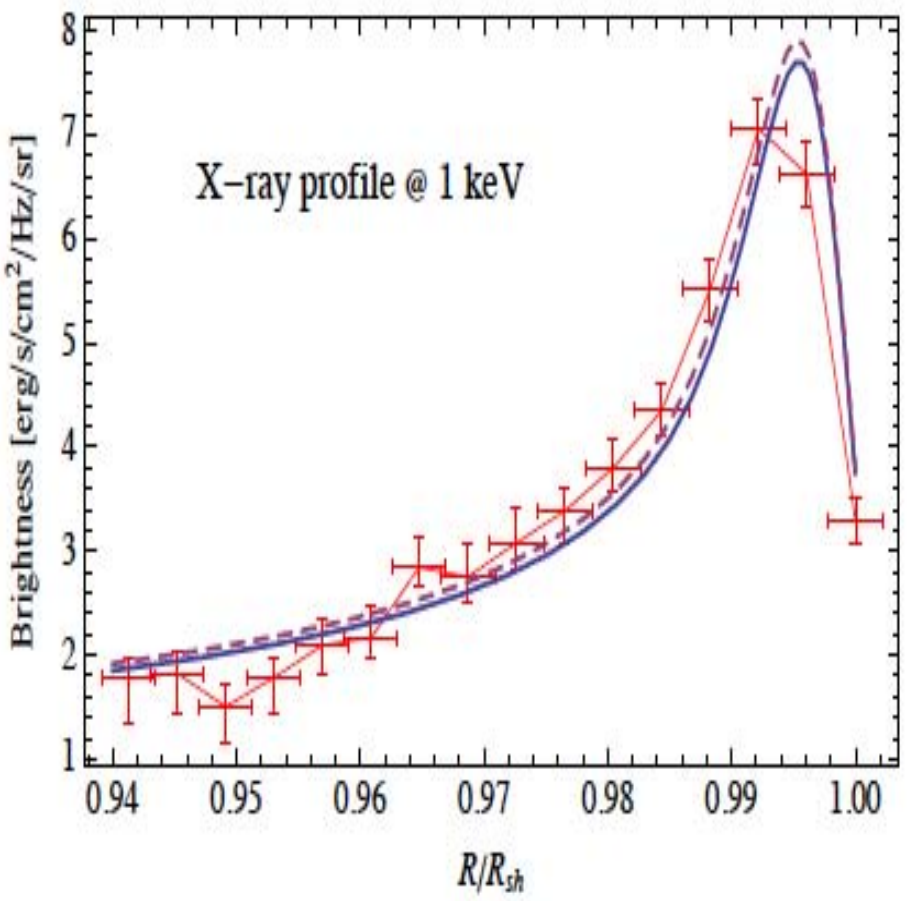
$$\tilde{r} = \frac{u_1 + v_{A,1}}{u_2 + v_{A,2}} \qquad \alpha = \frac{\tilde{r} + 2}{\tilde{r} - 1}$$

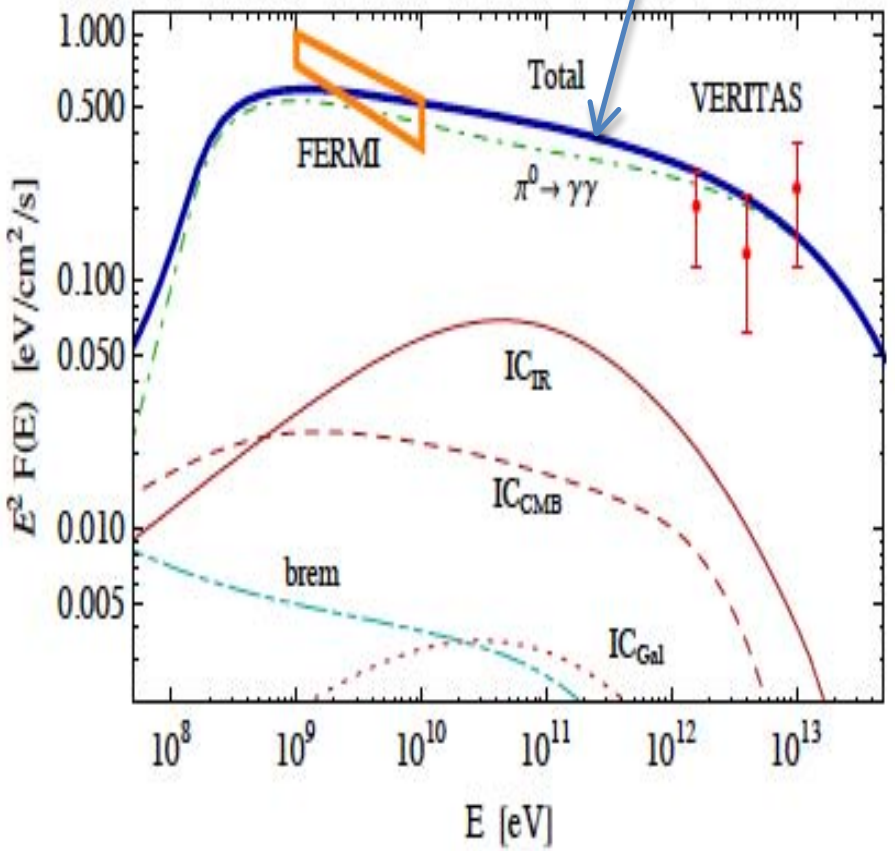


# The case of Tycho

Morlino&Caprioli 2011
(see also poster 145)

**STEEP SPECTRUM BASICALLY IMPOSSIBLE TO EXPLAIN WITH LEPTONS**




SEE ALSO POSTER 135, 146 FOR FERMI DATA ON TYCHO

# CR ESCAPE AND CLOUDS

**TWO SCENARIOS:**

***SNR SHOCK ENTERS THE MC***

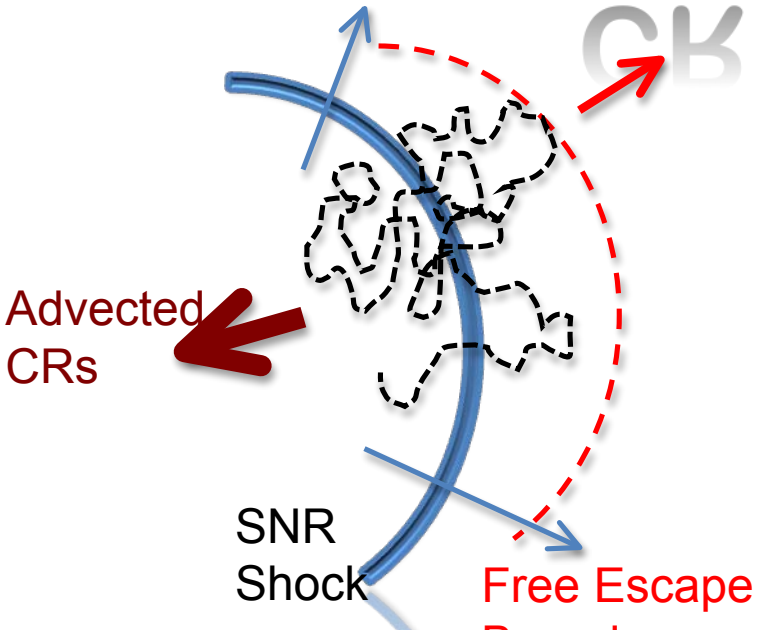
**Collisionless shock only involves the small fraction of Ions (low density)**

**Ion-neutral density kills waves→low $E_{max}$**

***MC IS ILLUMINATED BY CR FROM SNR***

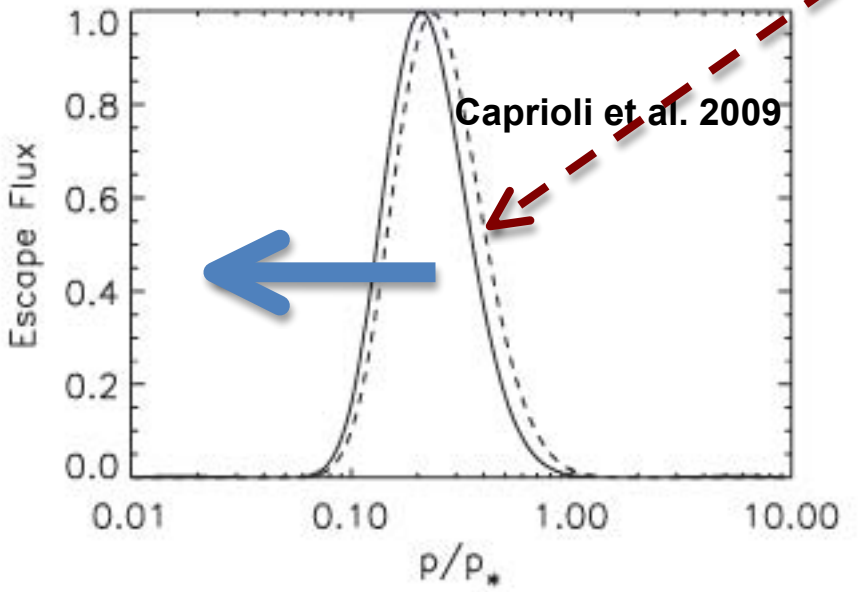
**The mc only acts as a target for pp**
**Gamma ray flux depends on**
**-Age of SNR**
**-Diffusion coefficient around the SNR**
**-Escape physics**

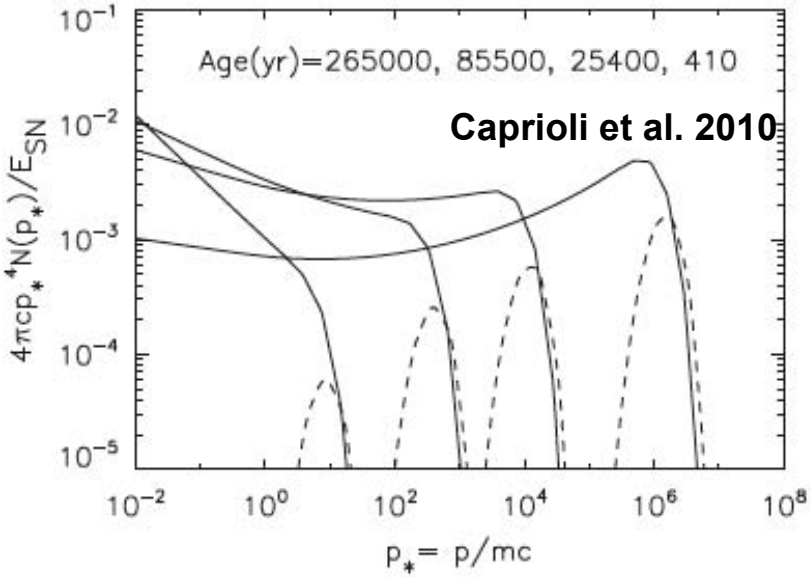
# CR ESCAPE




**The escape flux can be calculated using the transport equation IF one assumes a free escape boundary surface (DURING ST PHASE)**

$$\Phi_{esc}(E,x) = D(E)\left(\frac{\partial f(E,x)}{\partial x}\right)_{x=x_{fe}}$$



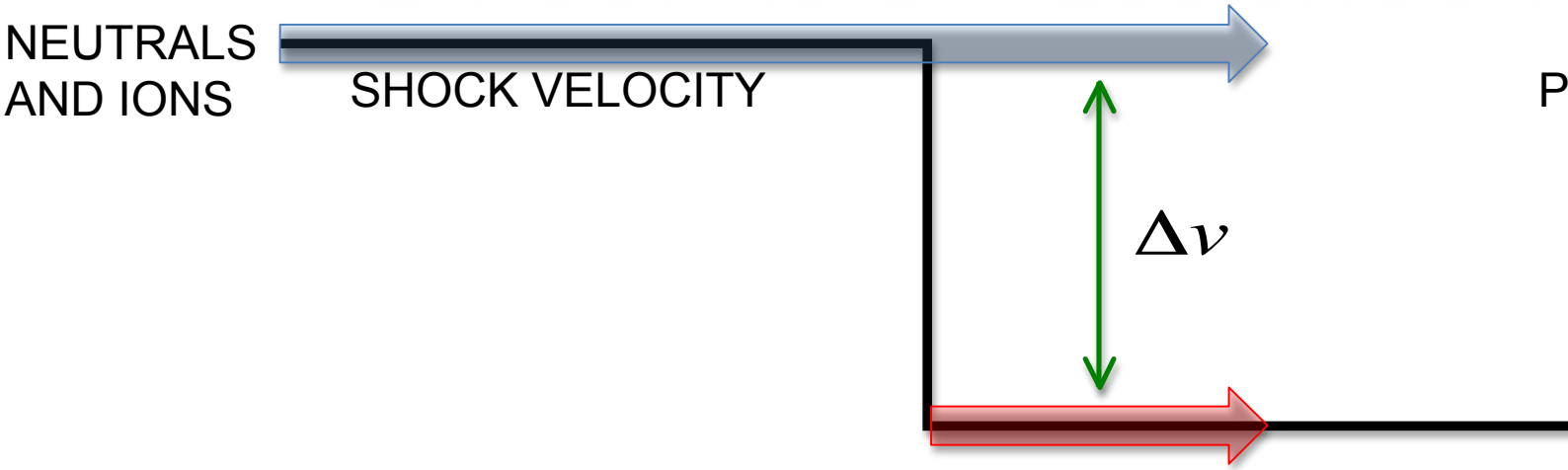



# SOME RECENT AND POSSIBLY FUTURE DEVELOPMENTS

## *COLLISIONLESS SNR SHOCKS IN PARTIALLY IONIZED MEDIA:*

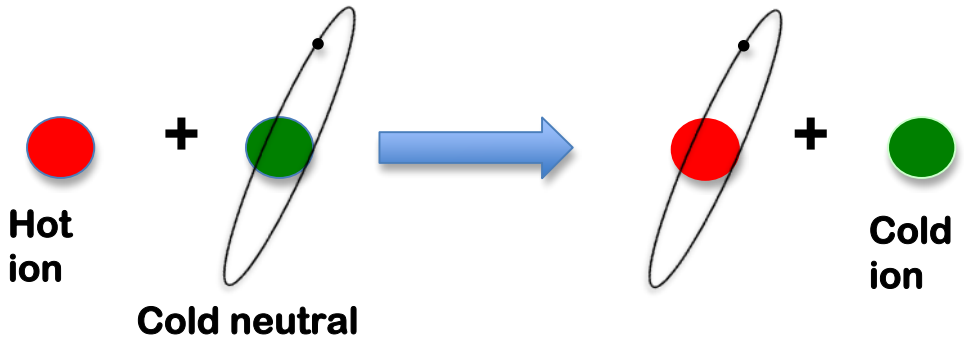
### *Anomalous width of Balmer lines*

# SUBTLE ASPECTS OF ACCELERATION AT A COLLISIONLESS SHOCK



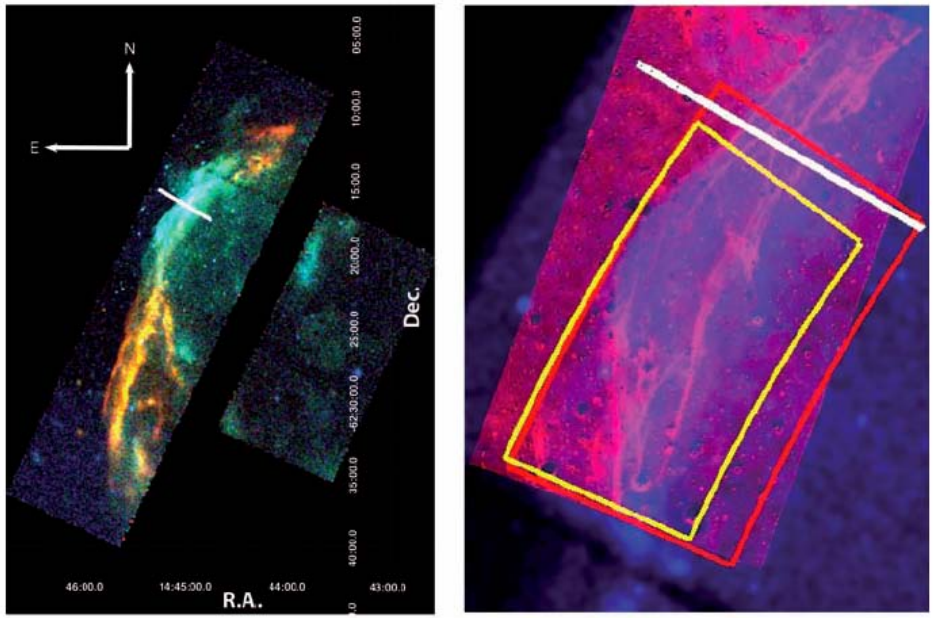

PB+, 2011

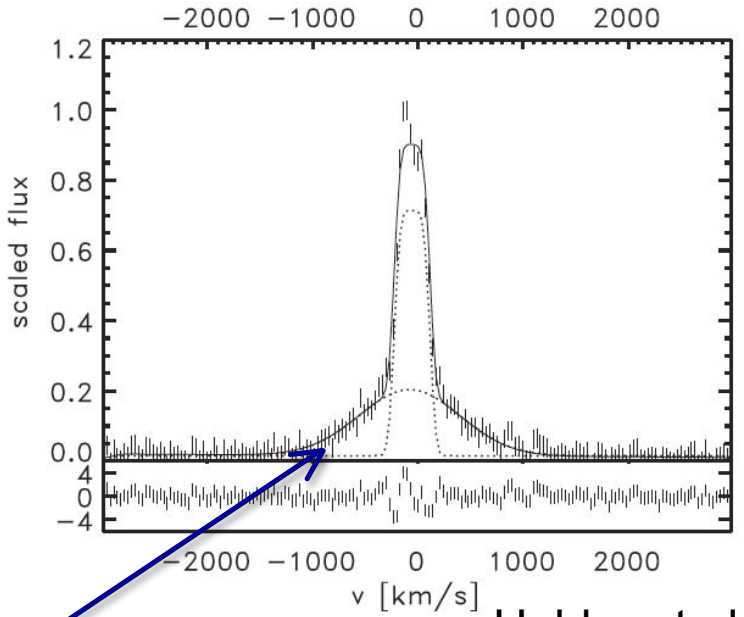
**CHARGE EXCHANGE**
**→ BROAD BALMER LINE**
**(NEUTRALS THAT MADE CHARGE EXCHANGE)**
**REFLECTING THE TEMPERATURE OF IONS…**




**BUT THE LATTER AFFECTED BY EFFICIENT CR ACCELERATION**

# BROAD BALMER LINES NARROWER THAN FOR UNMODIFIED SHOCKS




Helder et al. 2009

$$W_{broad} = \sqrt{8 \ln 2 \frac{kT_2}{m}} \approx 1.02\ v_{sh}$$

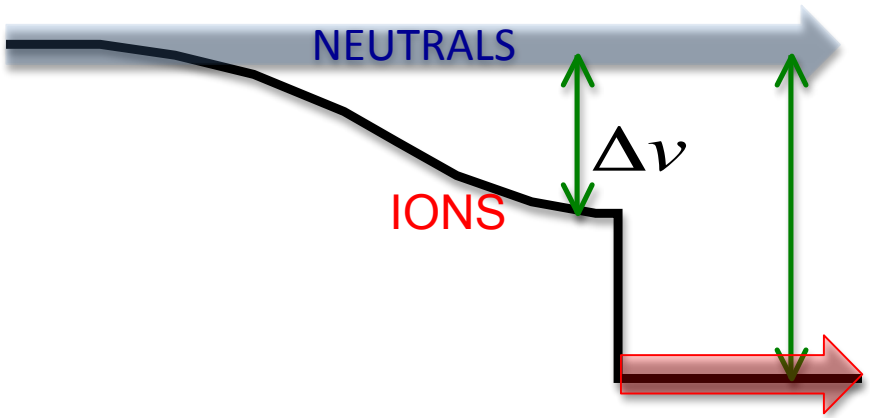
$$W_{broad} = 1100 \pm 63\,km/s \rightarrow T_2 = 2.3 \pm 0.3\,keV$$

Shock speed from proper motion

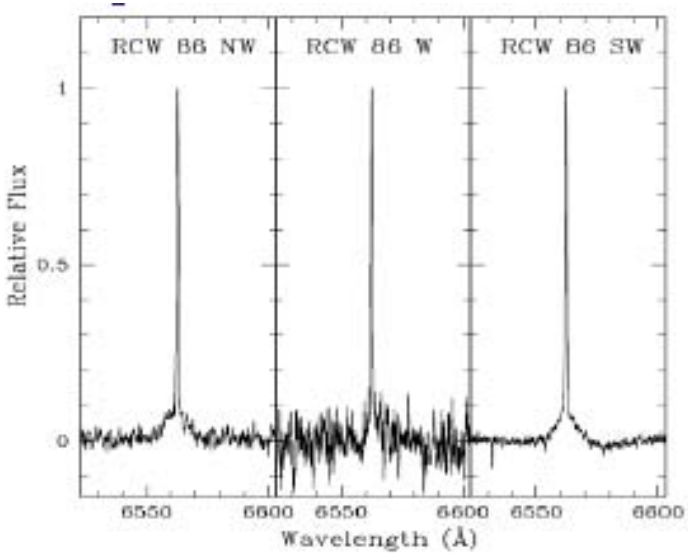
$$v_{shock} = 6000 \pm 2800\,km/s \left(\frac{d}{2.5 \pm .5\,kpc}\right) \left(\frac{\dot{\theta}_{obs}}{0.5 \pm .2''\,yr^{-1}}\right) \rightarrow T_2 = \begin{array}{l} 20-150\,keV\,(no\,equilibration) \\ 12-90\,keV\,(equilibration) \end{array}$$

**INFERRED EFFICIENCY of CR ACCELERATION 50-60% !!! (BUT model dependent)**

# NARROW BALMER LINES BROADER THAN FOR UNMODIFIED SHOCKS




Sollerman et al. 2003




**CHARGE EXCHANGE OCCURS NOW IN THE CR INDUCED PRECURSOR**

$$W_{broad} = \sqrt{8 \ln 2 \frac{kT_0}{m}} \approx 21 \text{ km/s} \left( \frac{T_0}{10^4 K} \right)^{1/2}$$

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

**NARROW BALMER LINE IS EXPECTED TO BE BROADER THAN FOR AN UNMODIFIED SHOCK**

# SUMMARY

- ◎ REQUIRED POWER → NON LINEAR THEORY OF ACCELERATION
- ◎ MAGNETIC FIELD AMPLIFICATION → MOST LIKELY CR INDUCED
- ◎ EFFICIENT ACCELERATION SEEN IN SIZE OF X-RAY FILAMENTS, ABSENCE OF X-RAYS FROM PRECURSOR, EMAX @ KNEE, ANOMALOUS BALMER LINE WIDTHS
- ◎ ANISOTROPY SUGGESTS $\delta \sim 1/3$ → INJECTION SLOPE 2.3-2.4
- ◎ GAMMA RAYS ALSO SUGGEST STEEP INJECTION → PROBABLY ACTION OF SCATTERING CENTERS SPEED, BUT ALSO NEUTRALS
- ◎ TYCHO PROBABLY THE FIRST UNAMBIGUOUS HADRONIC SOURCE
- ◎ IN GENERAL EFFICIENT ACCELERATION DOES NOT IMPLY GAMMA
- ◎ AS A BY-PRODUCT OF SNR PARADIGM → TRANSITION TO EXTRA GALACTIC CR AT $10^{18}$ eV, NOT @ ANKLE