

13<sup>th</sup> AGILE workshop  
May 25-26, 2015, Rome

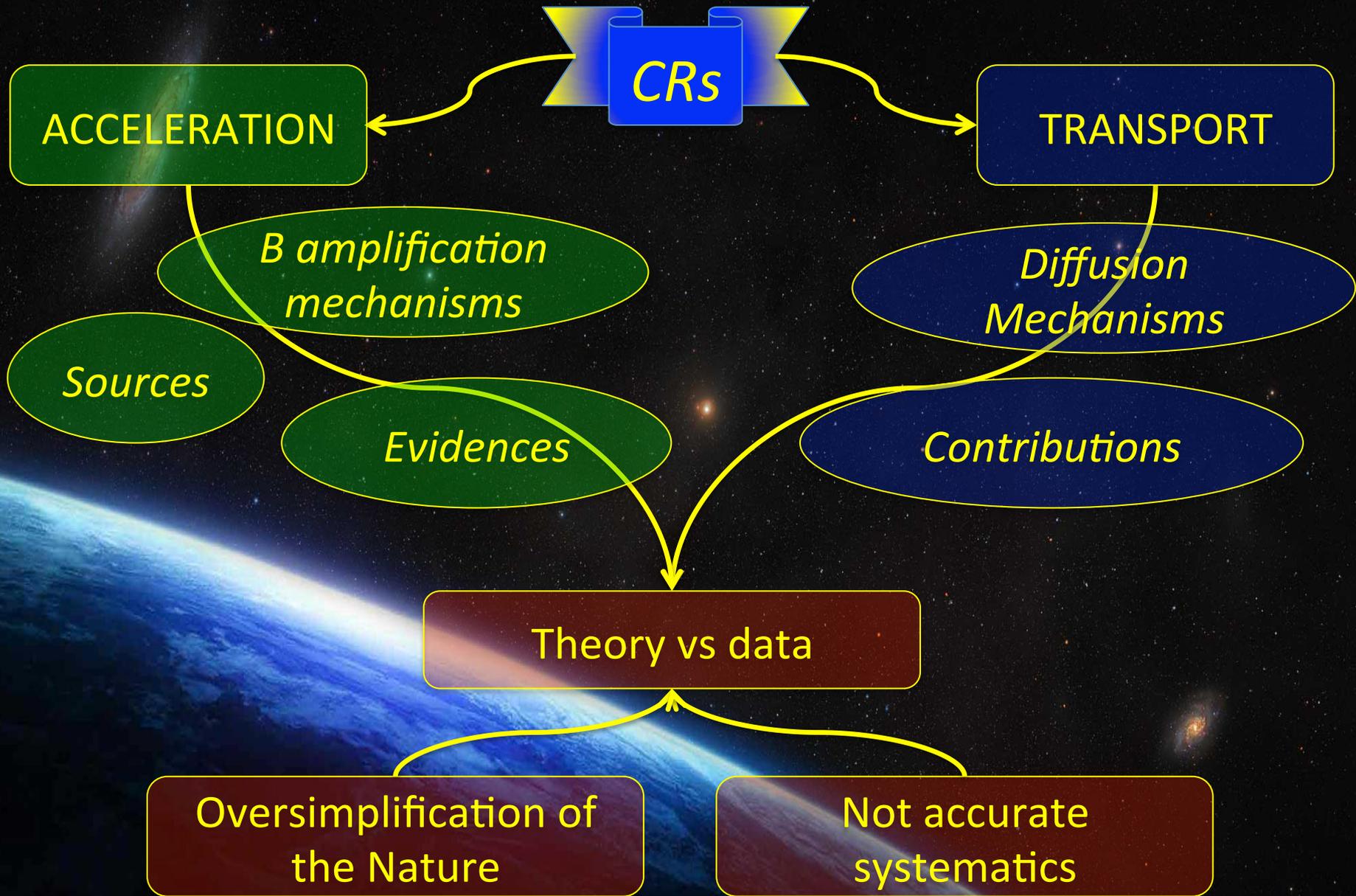


Particles and gamma-ray  
tell us about  
CR acceleration from SNRs

*Martina Cardillo*

INAF-Osservatorio Astrofisico di Arcetri

# THE THREE OF CR ISSUE



# SNAPSHOT

## Supernova Remnants

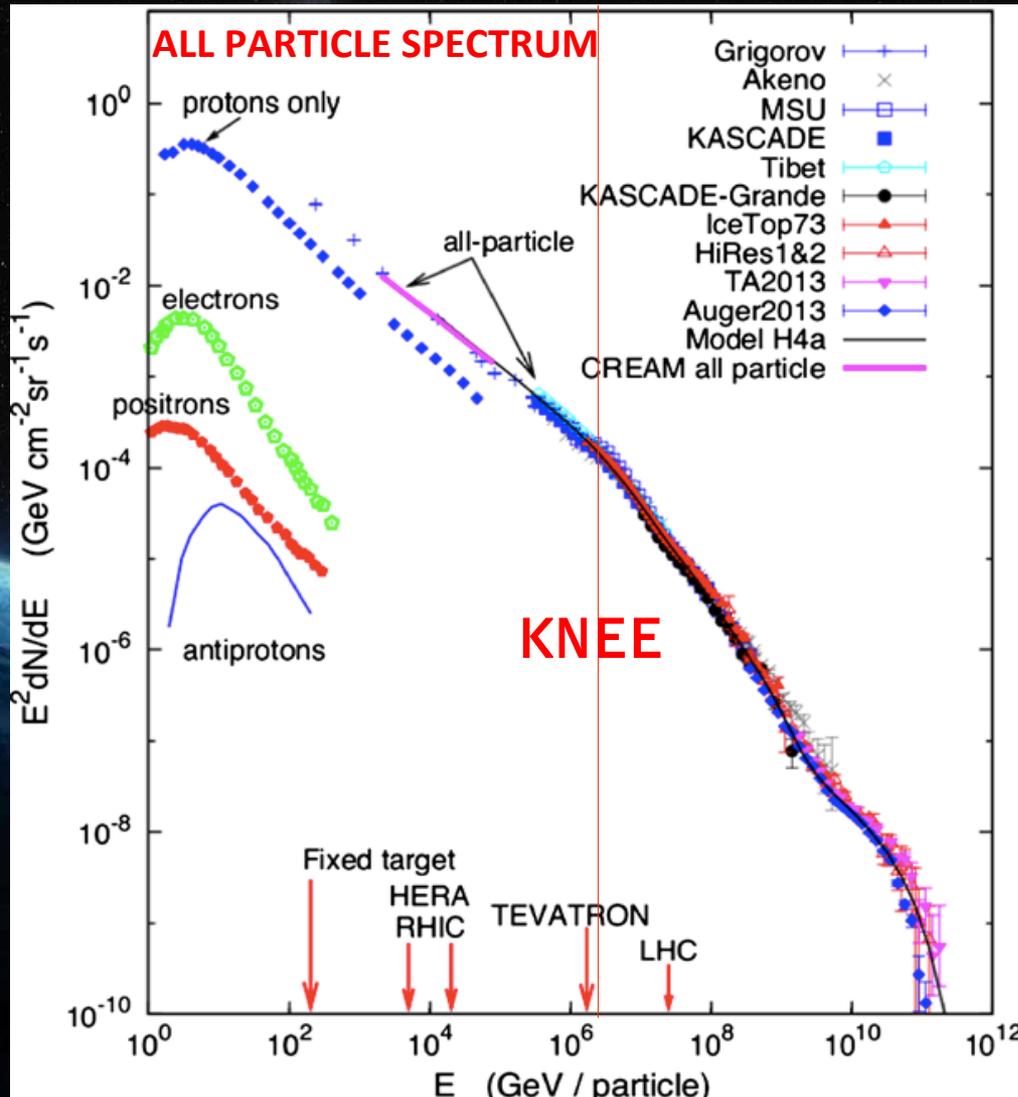
- Energetic shock waves
- Possibility of energy gains by repeated shock crossing



**DIFFUSIVE FERMI  
ACCELERATION  
(MAGNETIC TURBULENCE)**



**AMPLIFIED  
MAGNETIC FIELD  
UPSTREAM**



# RESONANT & NON-RESONANT INSTABILITY

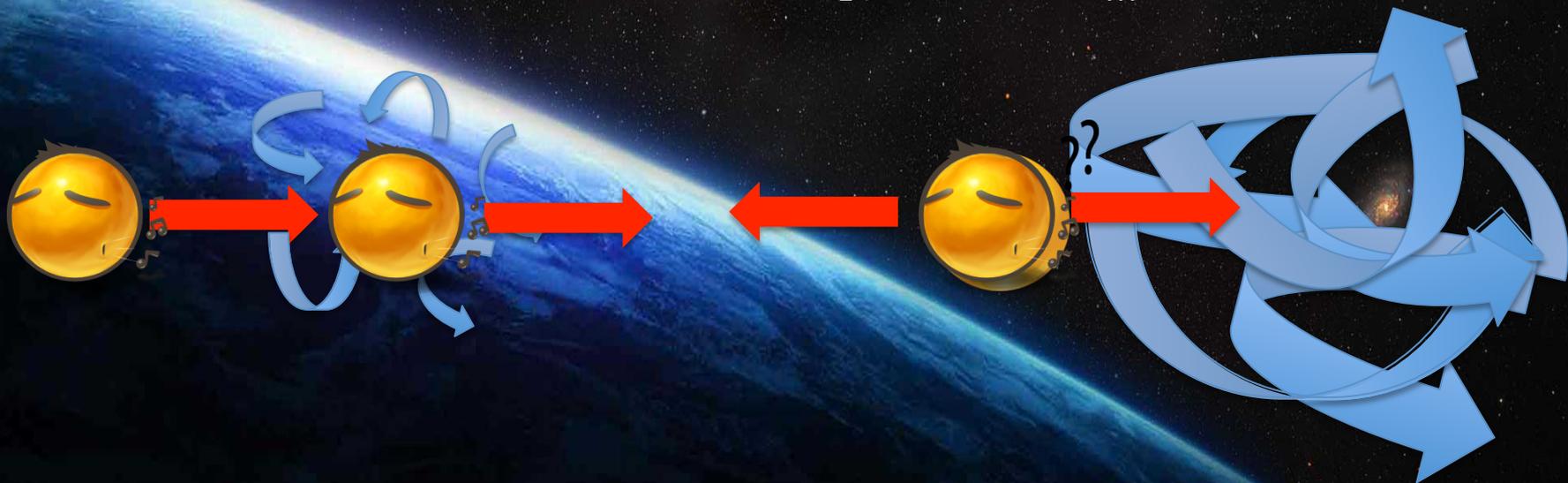
AMPLIFIED  
MAGNETIC FIELD  
UPSTREAM

RESONANT  
INSTABILITY  
(Skilling 1975)

Excitation of Alfvén waves with  $\lambda \approx r_L$   
→ saturation at  $\delta B/B \approx 1$   
→  $E_M < 1$  PeV

NON  
RESONANT  
INSTABILITY  
(Bell 2004)

Purely growing waves at wavelengths  
 $\lambda \ll r_L$ , driven by the CR current  $j_{CR}$   
generating power at larger scales up  
to  $\lambda \approx r_L$  → larger  $E_M$

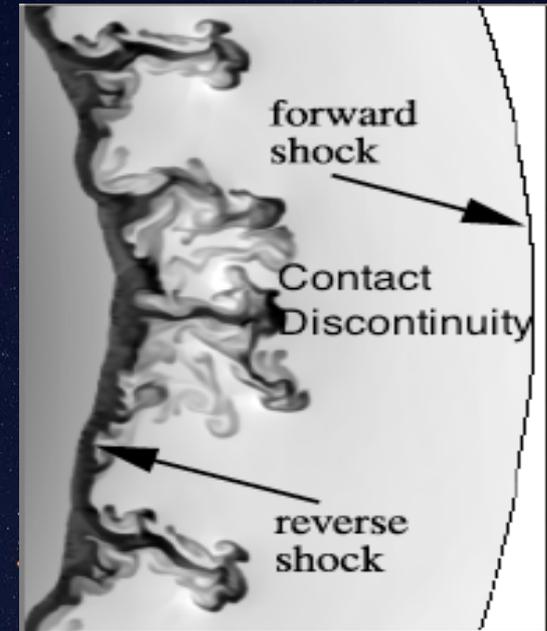


# ACCELERATION EVIDENCES: X-rays

➤ Distance between Contact Discontinuity and Blast Wave

→ compression ratio

e.g. Tycho [Warren et al. 2005]



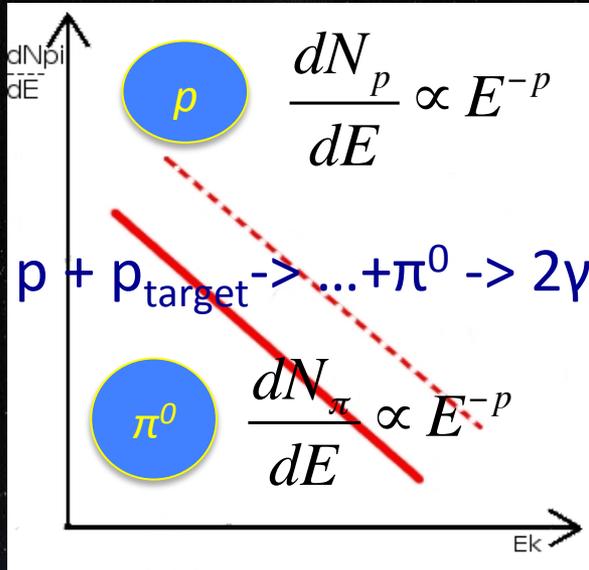
➤ Amplification of the magnetic field :

→ X-ray fast time variability: RXJ 1713 [Uchiyama et al. 2007]

→ Thickness of X-ray emitting region:

$$\sqrt{(D \tau_{\text{syn}})} \approx 0.04 (B_{-4})^{-3/2} \sim 0.01 \text{ pc}$$

# ACCELERATION EVIDENCES: Gamma-rays

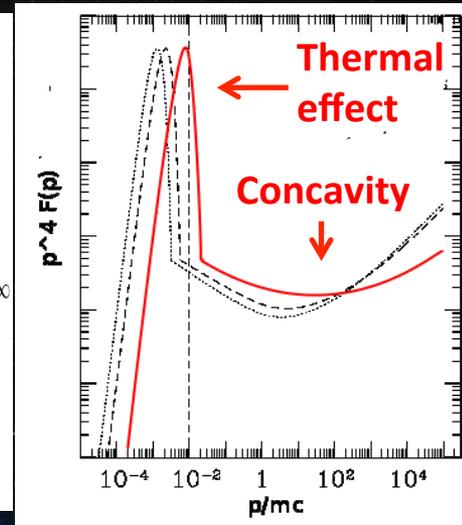
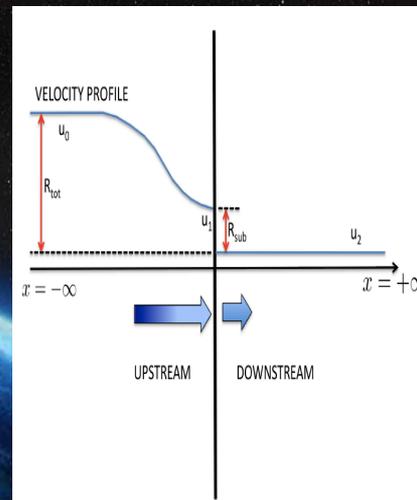


## LINEAR DSA

- Injection spectrum:  
 $Q(E) \cong E^{-p}$  ( $p=2$  for strong shocks)
- Escape spectrum:  
 $N(E) \cong E^{-(p-\delta)}$  ( $D(E) \cong E^{\delta}$  with  $\delta=[0.3,0.7]$ )

## Non LINEAR DSA

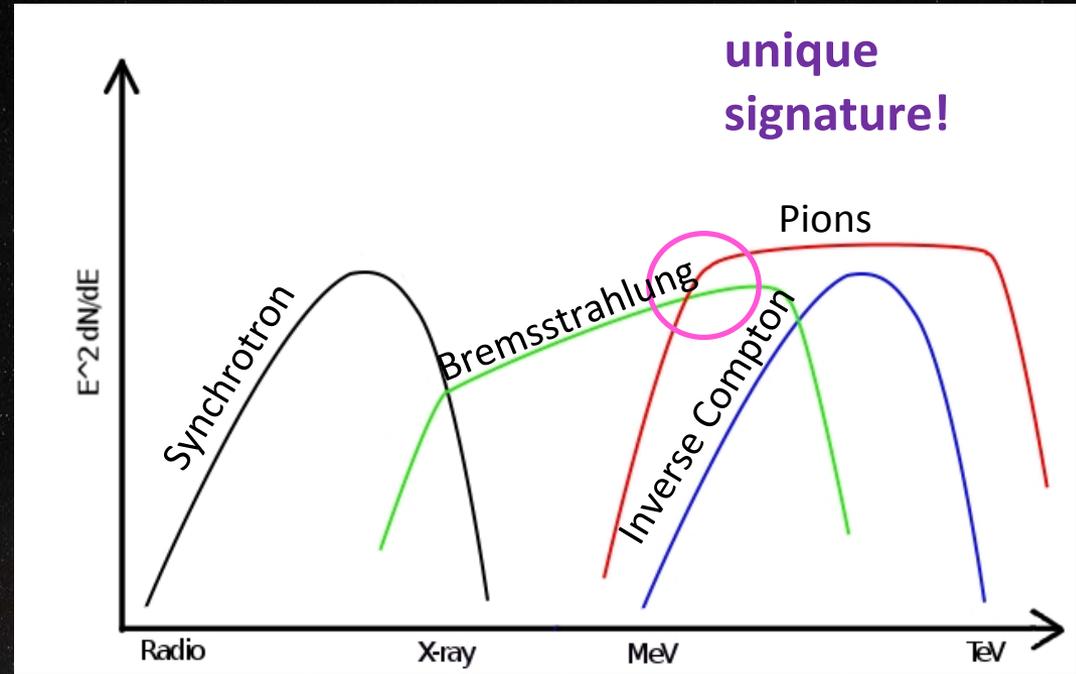
- Existence of a precursor
  - Concavity of the spectrum
  - Lower downstream temperature
- SN1006 & RCW86 [Vink 2011]



# ACCELERATION EVIDENCES: Gamma-rays

➤ Pion bump

➤ Pevatrons:  
from NR Bell instability



ISM

$$E_M(R) \cong \frac{2Ze}{10} \sqrt{4\pi\rho R^2} \frac{\xi_{CR}}{c\Lambda} v_{sh}^2(R) = 130 \left( \frac{\xi_{CR}}{0.1} \right) \left( \frac{M_{ej}}{M_\odot} \right)^{-2/3} \left( \frac{E_{SN}}{10^{51} \text{ erg}} \right) \left( \frac{n_{ISM}}{\text{cm}^{-3}} \right)^{1/6} \text{ TeV}$$

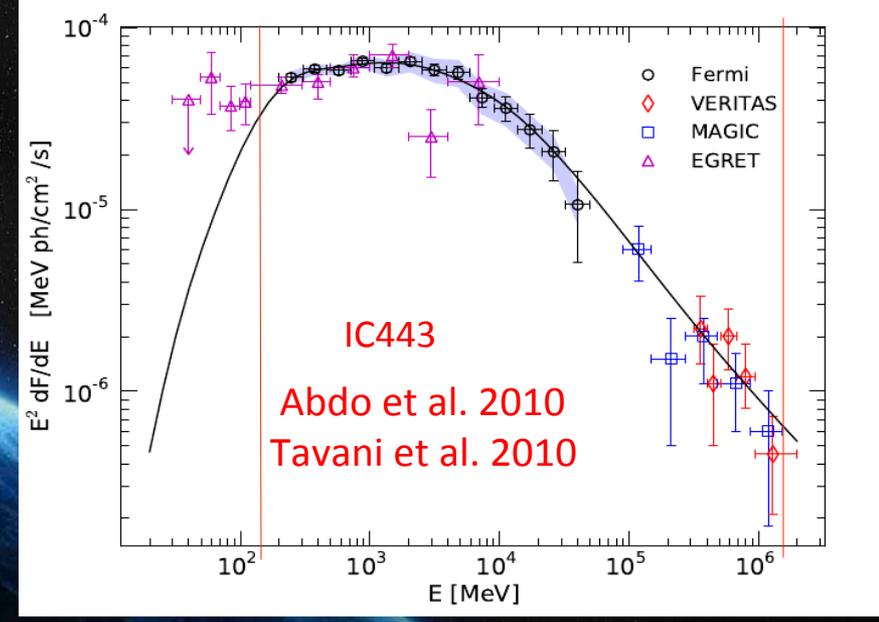
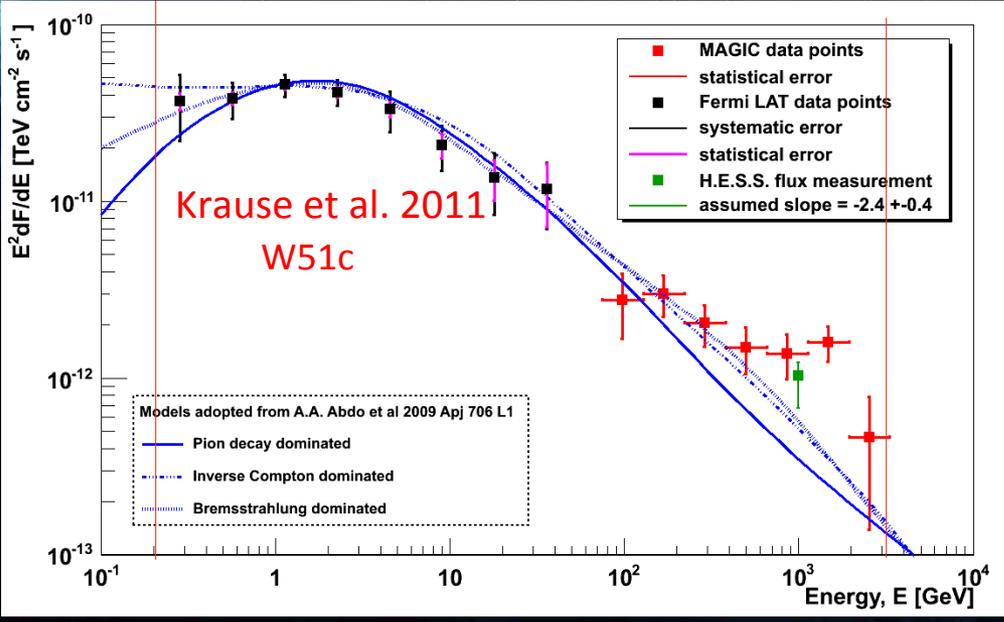
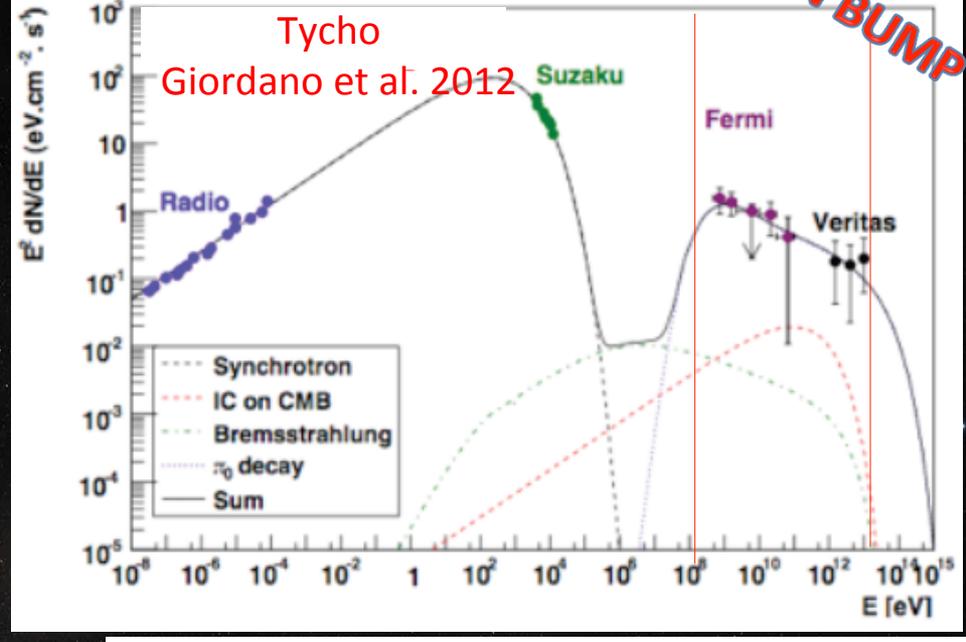
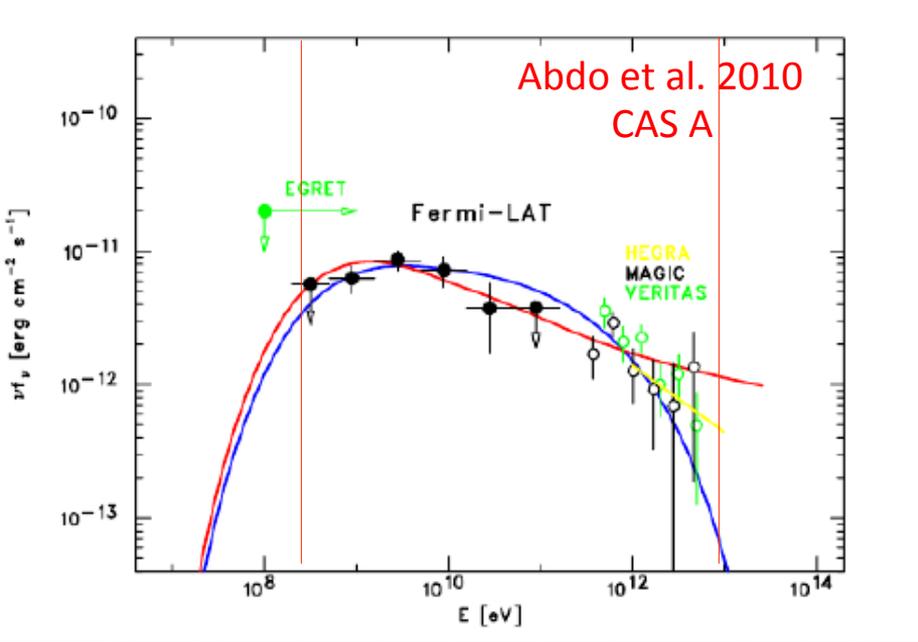
Cardillo, Amato & Blasi 2015

WIND

$$E_M(R) \cong \frac{2Ze}{5} \sqrt{4\pi\rho R^2} \frac{\xi_{CR}}{c\Lambda} v_{sh}^2(R) = 1 \left( \frac{\xi_{CR}}{0.1} \right) \left( \frac{M_{ej}}{M_\odot} \right)^{-1} \left( \frac{E_{SN}}{10^{51} \text{ erg}} \right) \left( \frac{\dot{M}}{10^{-5} \text{ km/yr}} \right)^{1/2} \left( \frac{V_w}{10 \text{ km/s}} \right)^{-1/2} \text{ PeV}$$

# CHALLENGES FROM Gamma-rays

PION BUMP

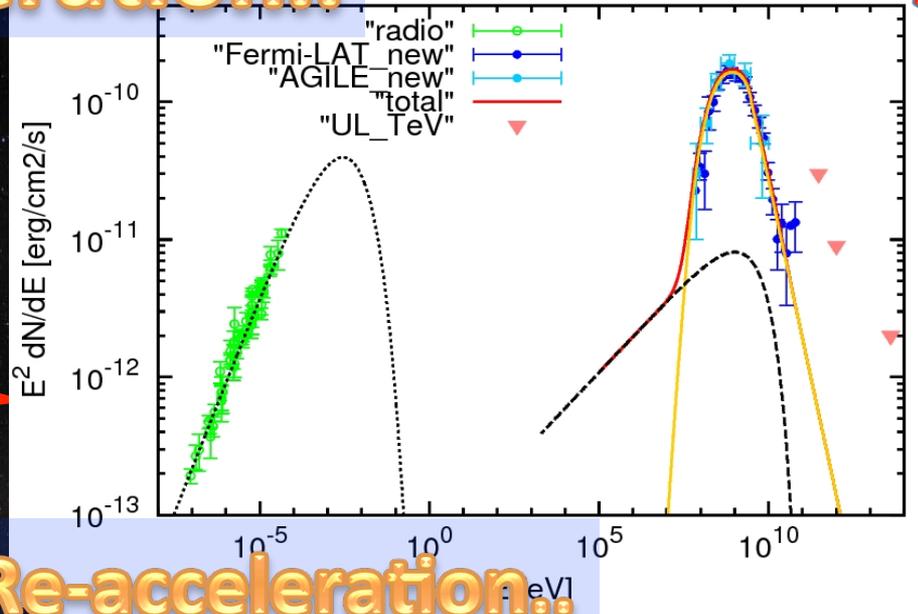
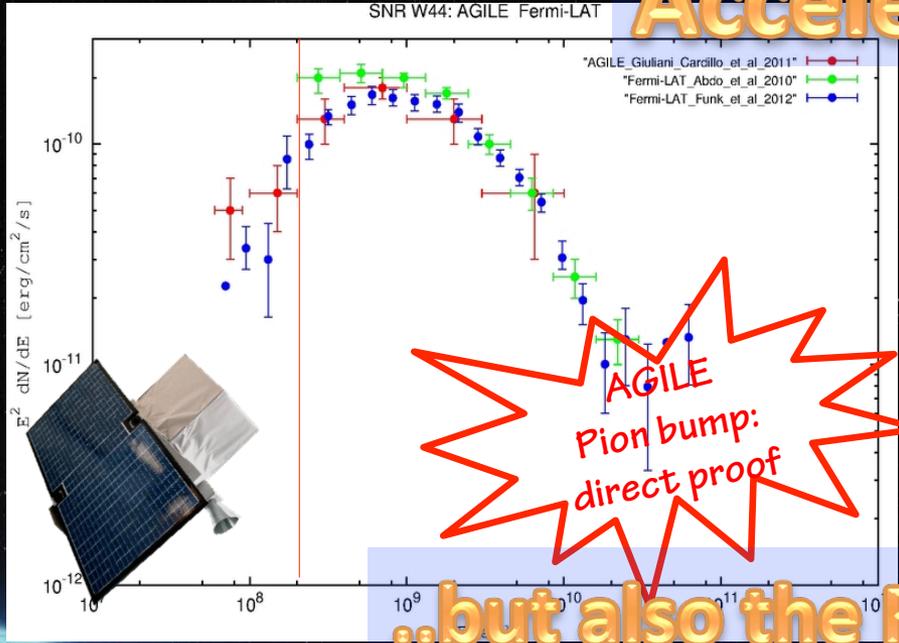


# CHALLENGES FROM Gamma-rays

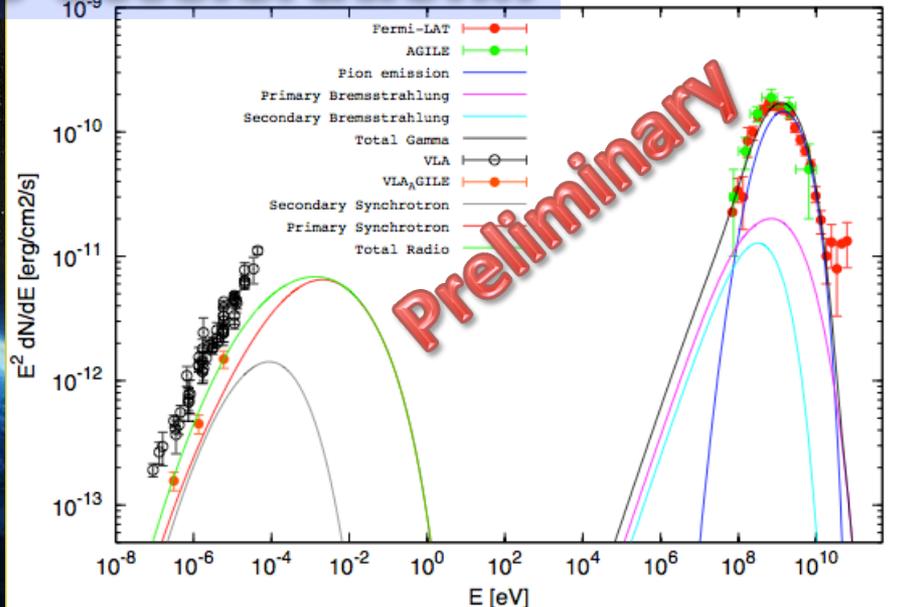
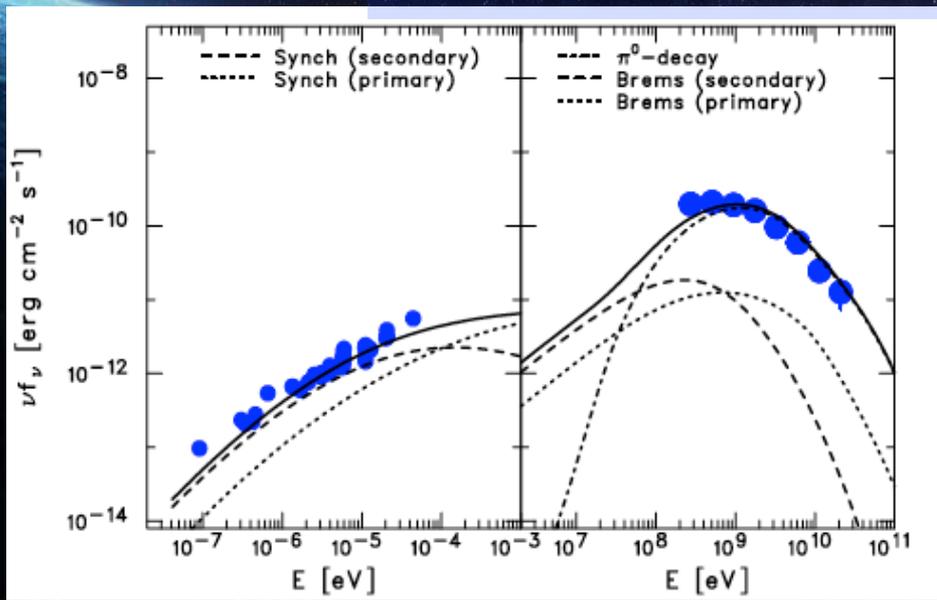
PION BUMP

## Acceleration..

Cardillo et al. 2014



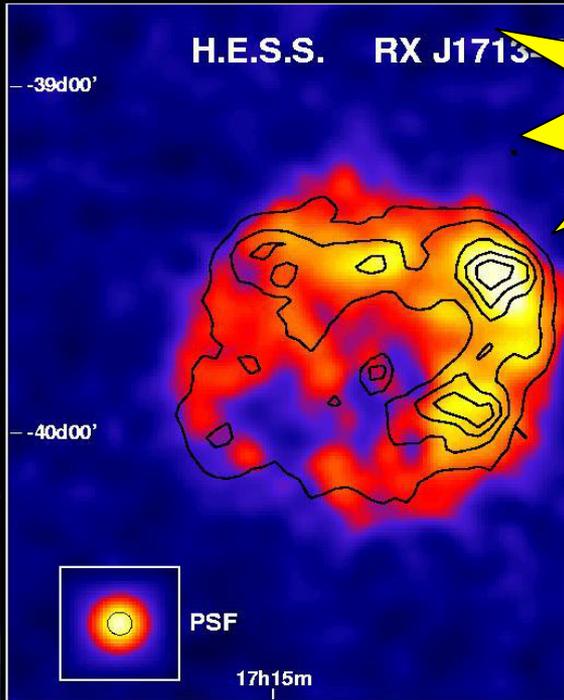
## ..but also the Re-acceleration..



Uchiyama et al 2010

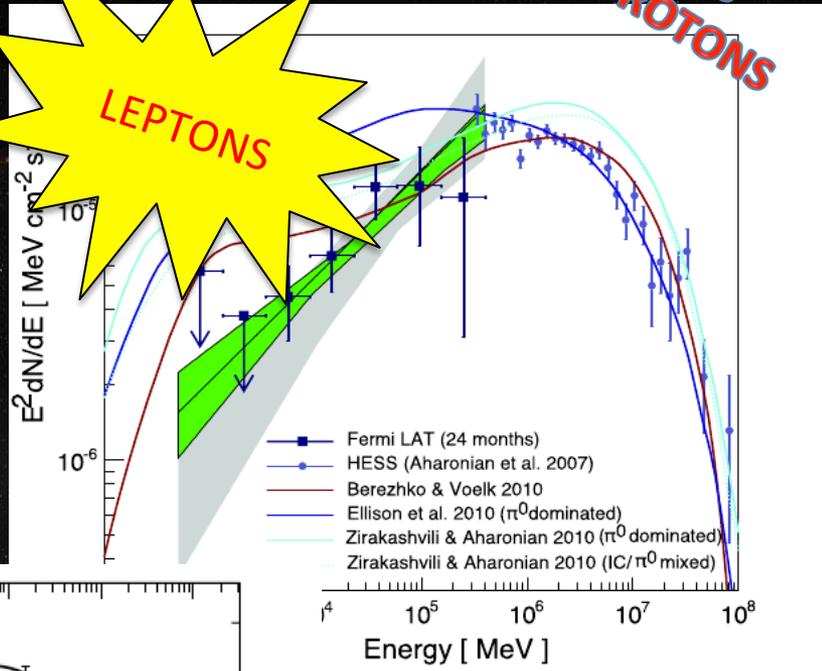
# CHALLENGES FROM Gamma-rays

ELECTRON  
VS  
PROTONS



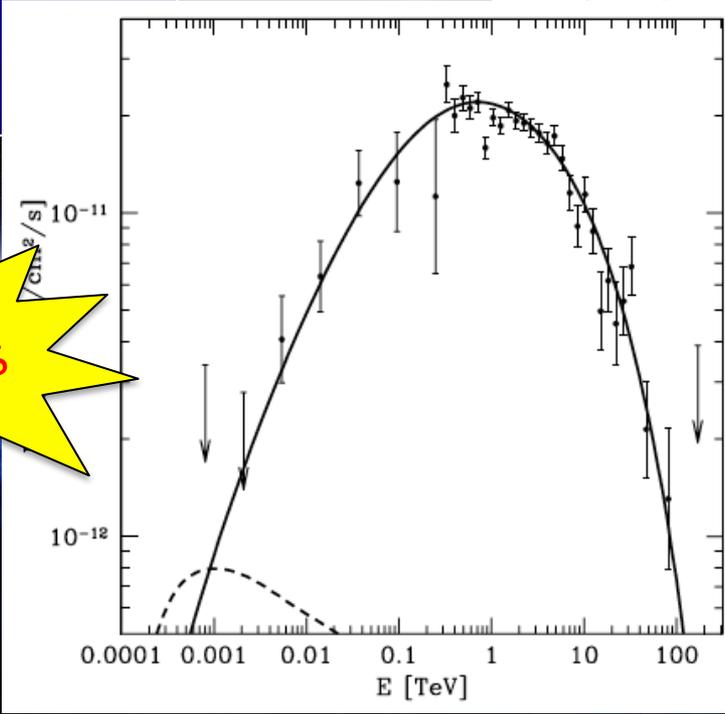
HADRONS

LEPTONS



Aharonian et al. 2007

HADRONS



Abdo et al. 2011

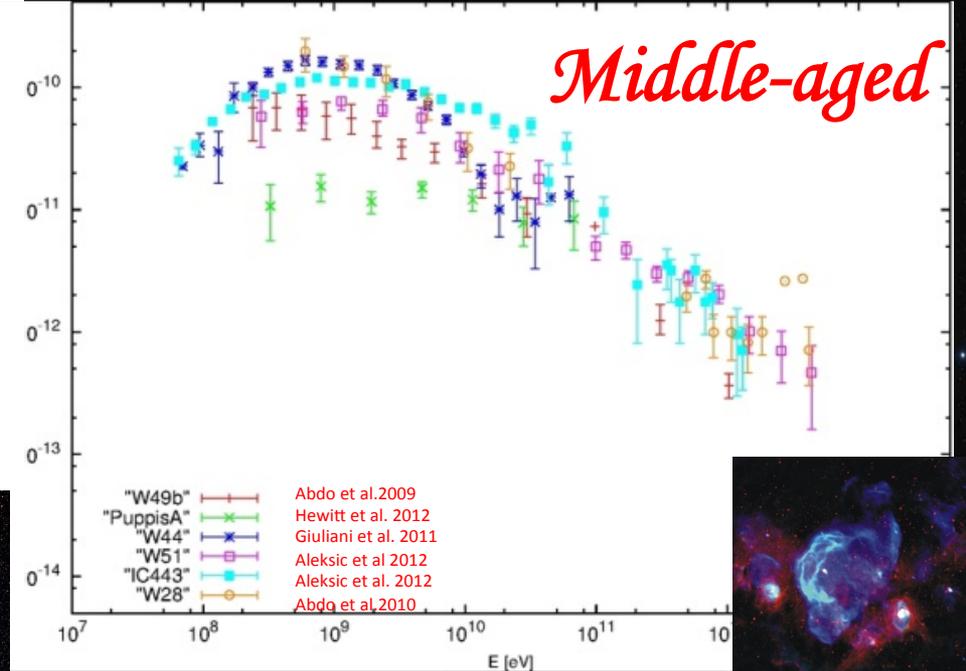
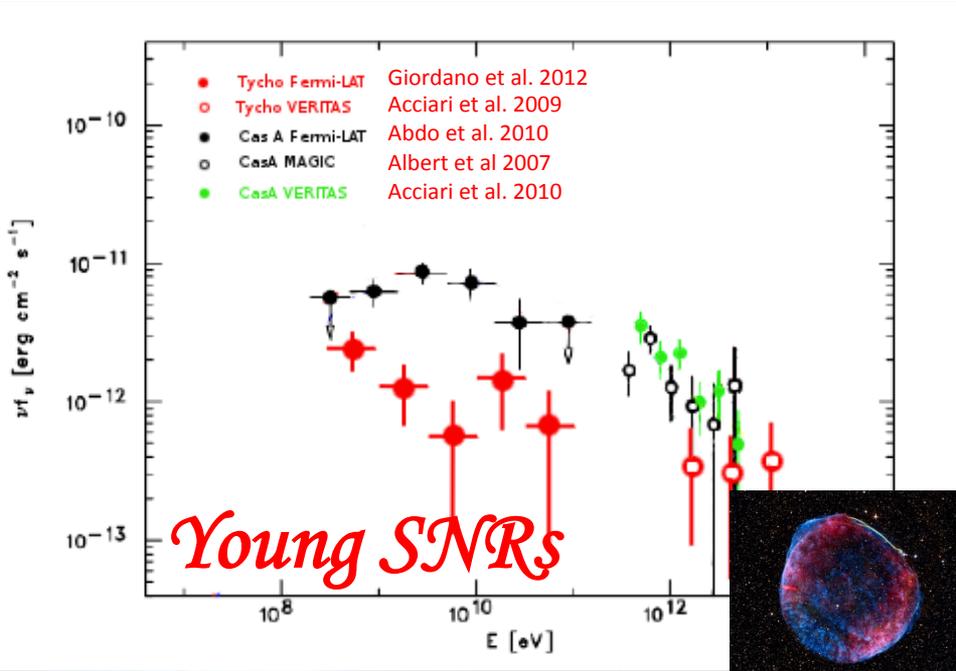
...even if  
the leptons  
maybe  
could...

Fukui et al. 2013  
Gabici & Aharonian 2014

# CHALLENGES FROM Gamma-rays

PEVATRONS

Cardillo et al. 2014b



## Young:

- Low-density medium
- $p = 2, 2-2, 4 \rightarrow$  No concavity!!
- No obvious Pevatrons

## Middle-aged:

- High-density medium
- $2, 6 < p < 3$
- No hope for Pevatrons !

# CHALLENGES FROM Gamma-rays

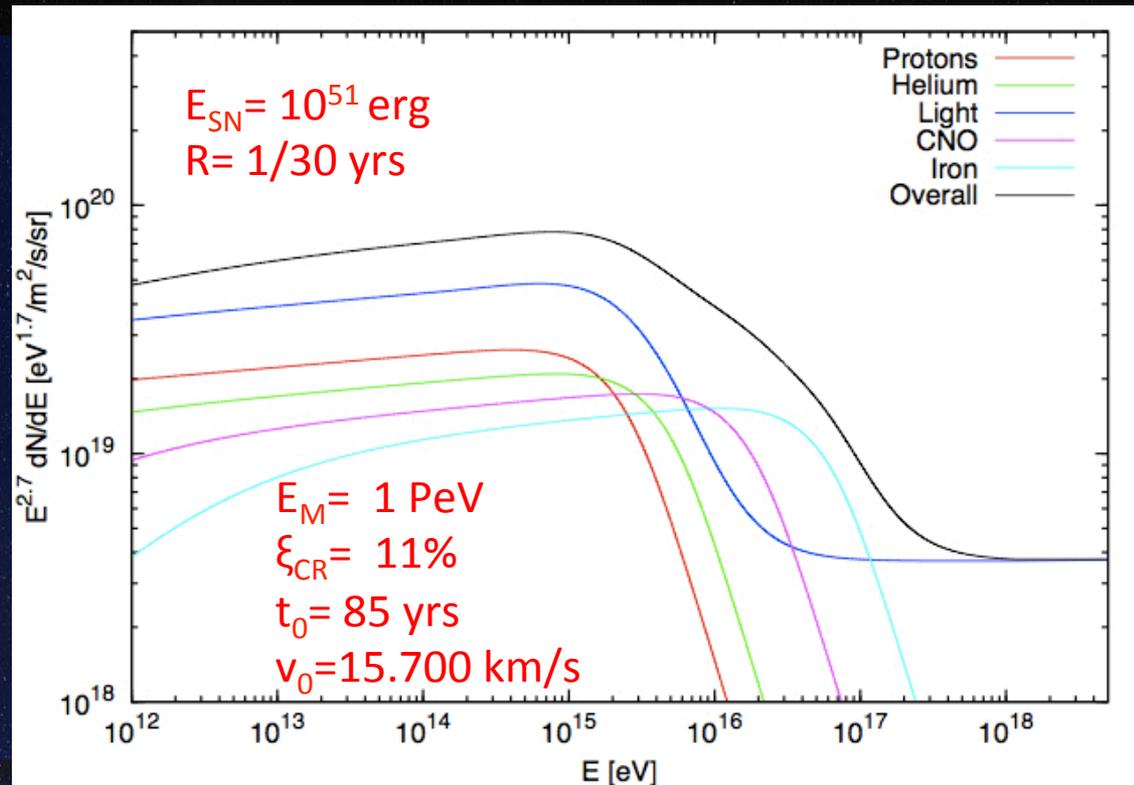
Cardillo, Amato & Blasi 2015

## WHY NO PEVATRONS?

THE HIGHEST ENERGIES ARE REACHED AT EARLY TIMES

IN FACT THE RELEVANT EPOCH FOR COPIOUS PARTICLES ACCELERATION AT PEV ENERGIES WOULD BE ~50 YEARS

VERY HARD TO OBSERVE DIRECTLY IN OUR GALAXY



## WHY STEEP SPECTRUM?

- VELOCITY OF SCATTERING CENTERS (Caprioli 2010)  $\rightarrow$  LOWER COMPRESSION RATIO
- NEUTRAL RETURN FLUX (Blasi 2012, Morlino 2013)
- STEEPER INJECTION INDEX DUE TO A LOWER DIFFUSION ENERGY DEPENDENCE (Blasi 2012)

# WHAT FROM BALMER LINES?

NEUTRAL  
RETURN FLUX

In the presence of **PARTICLE ACCELERATION**:

*LOWER TEMPERATURE DOWNSTREAM & A PRECURSOR APPEARS UPSTREAM*

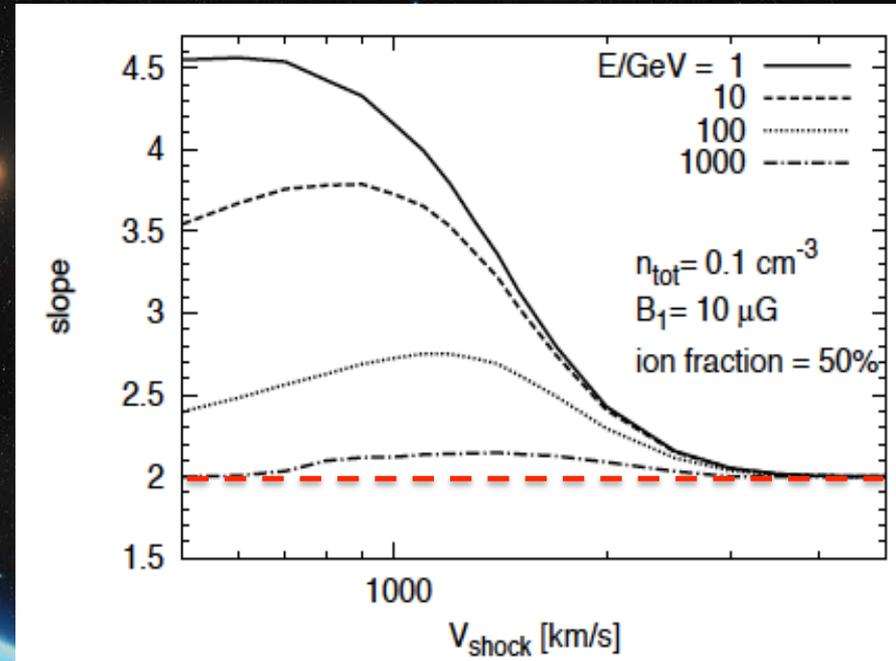
**BROAD** Balmer line get **NARROWER**

**NARROW** Balmer line gets **BROADER**

**Third INTERMEDIATE** line

Charge-Exchange between neutrals and ions with lower velocity → **NEUTRALS WHICH IS NOW FREE TO RETURN UPSTREAM**

**THIS NEUTRAL RETURN FLUX LEADS TO ENERGY AND MOMENTUM DEPOSITION UPSTREAM OF THE SHOCK!**



**LOWER COMPRESSION RATIO**

# WHAT FROM TRANSPORT?

STEEPER  
INJECTION INDEX

FROM B/C (secondary and primary elements, respectively)

→ INFORMATION ON DIFFUSION COEFFICIENT

$$\frac{\Phi_B(E)}{\Phi_C(E)} \propto X(E) \propto \frac{1}{D(E)} \sim E^{-\delta} \quad \Longrightarrow \quad 1/3 < \delta < 0.7$$

For relativistic E

ADDING THE DISCRETENESS OF THE SOURCES AND DATA ON CR FLUX ANISOTROPY (Blasi&Amato 2012)

$$\Delta_A \approx D(E)$$

$$\delta \approx 1/3$$

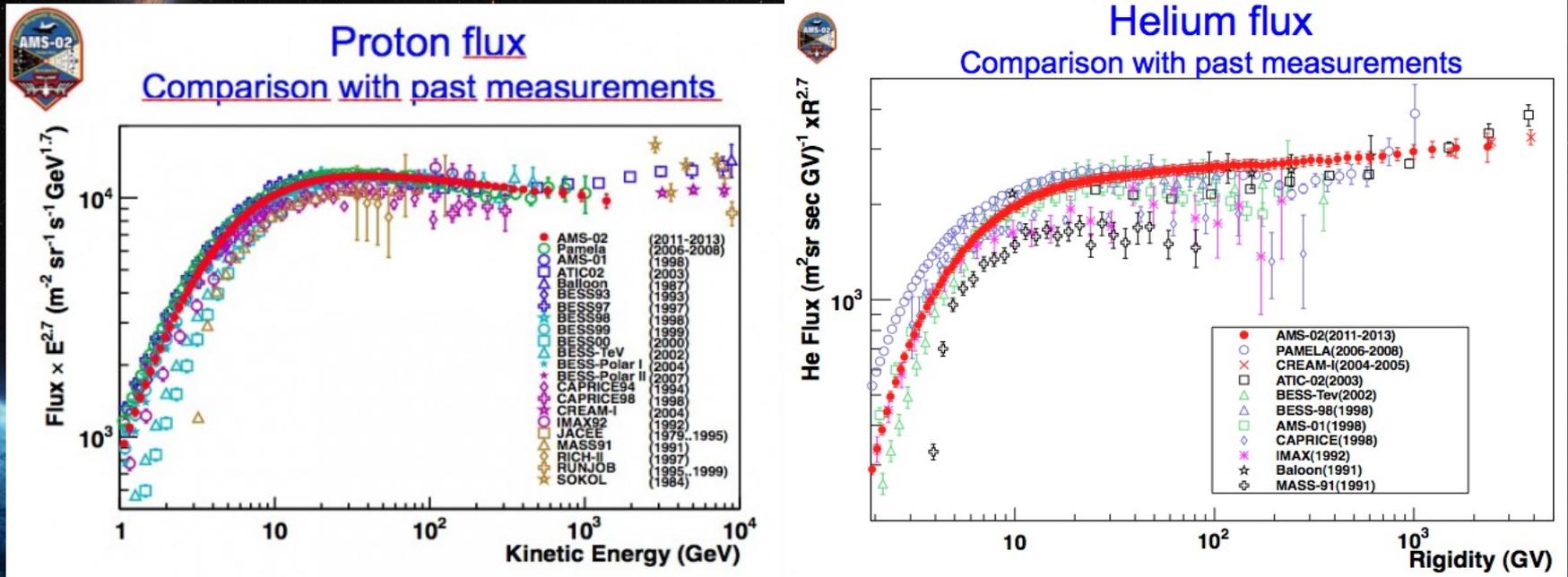
$$\gamma \approx 2.3-2.4$$

**WARNING!**

- UNCERTAINTIES ABOUT ANISOTROPY ESTIMATION (LOCAL EFFECTS)
- IMPORTANT SIMPLIFICATIONS ON THE NUMERICAL TRANSPORT MODEL

# CHALLENGES BY PARTICLES

## Proton & Helium spectral hardening



POSSIBLE SOLUTION (Blasi&Amato 2012, Neronov 2012)

→ change in the propagation regime due to different kinds of turbulence

OPEN ISSUE

→ why is there a difference between protons and helium?



# SUMMARY

IN SPITE OF THE AMOUNT OF DATA FROM GAMMA-RAYS AND FROM PARTICLE DETECTORS, CR ORIGIN IS STILL AN OPENING ISSUE:

- Very hard to find Pevatron
- Ambiguity between acceleration and reacceleration in the middle aged SNRs
- Inconsistence between theory and data
- Inconsistence between instrument results

- 
- New generation of gamma-ray instruments, expecially for the low-energies (ASTROGAM)
  - Multiwavelength analysis
  - Deeper understanding of acceleration and transport mechanisms
  - Need to focus on instrument systematics

Thank you  
very much!

