Propagation and Acceleration of Cosmic Rays: what Gamma Rays can say

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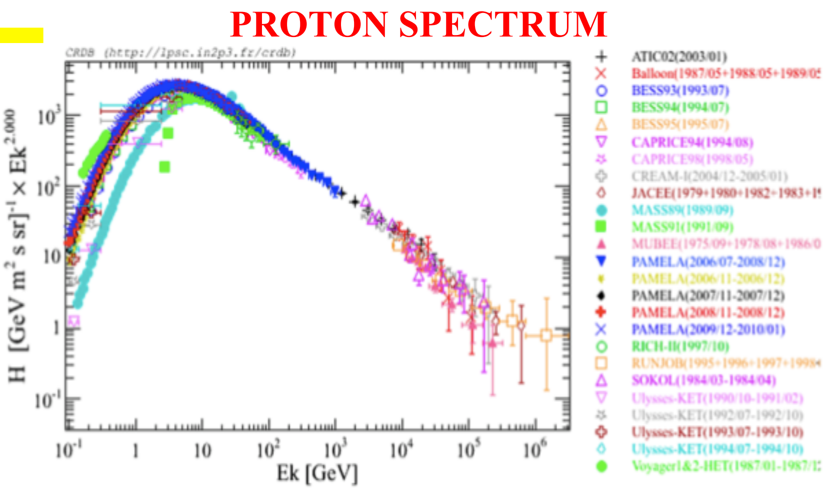
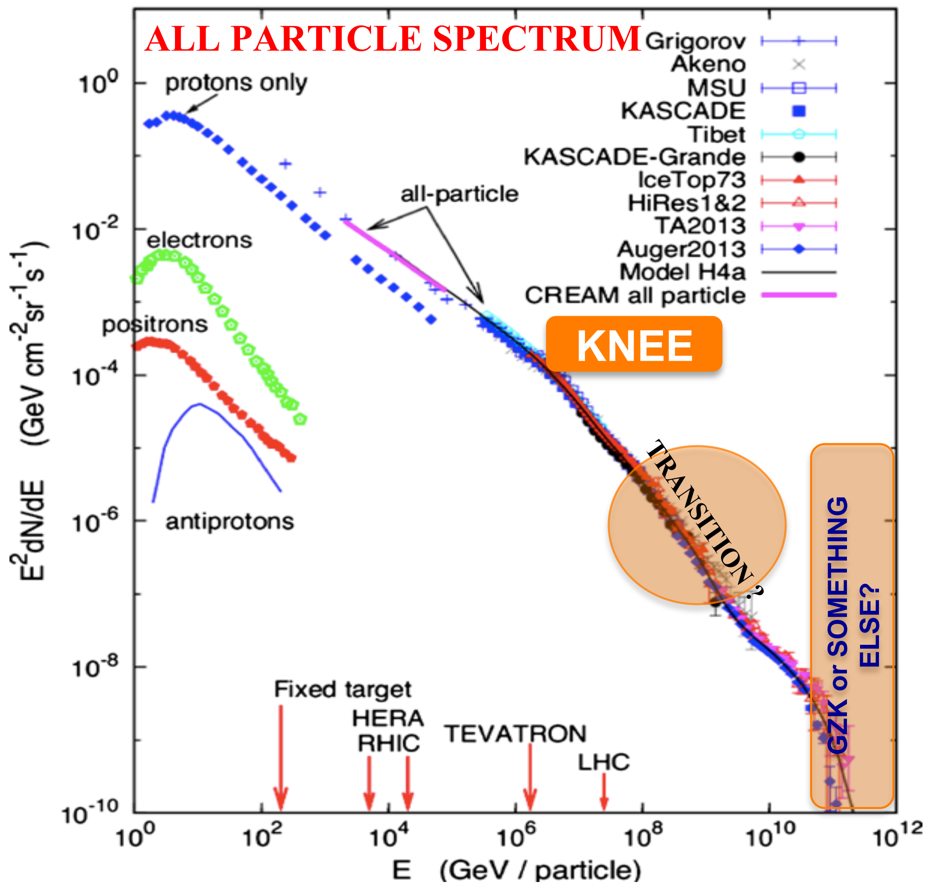
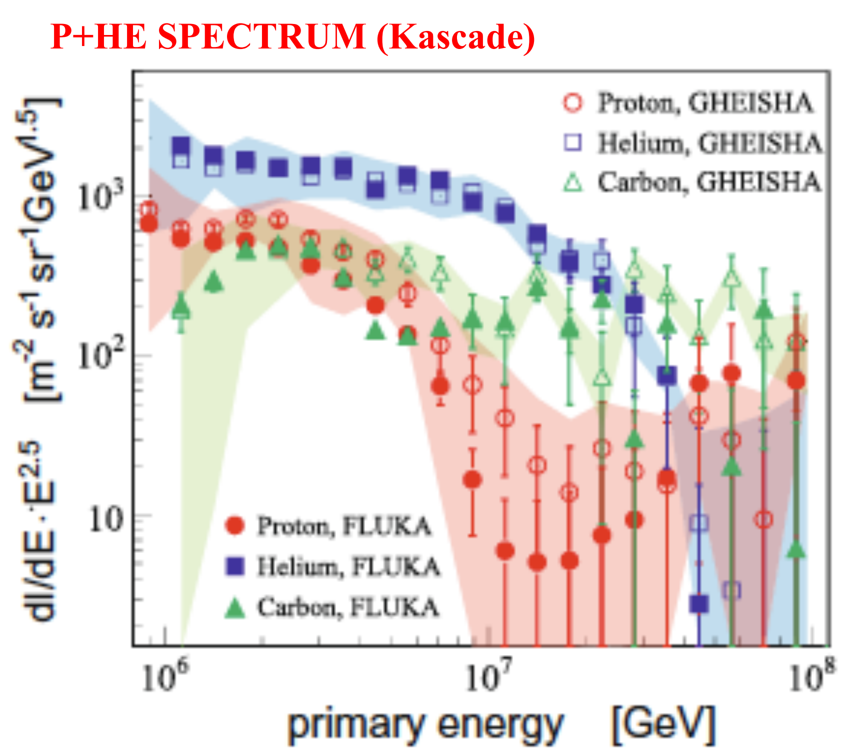
Galactic Cosmic Rays Spectra

- ✓ The all particle spectrum has a (broken) power law behavior with few structures: knee, ankle, strong suppression at UHE.
- ✓ Changes in chemical composition and origin (Galactic/Extra-Galactic)

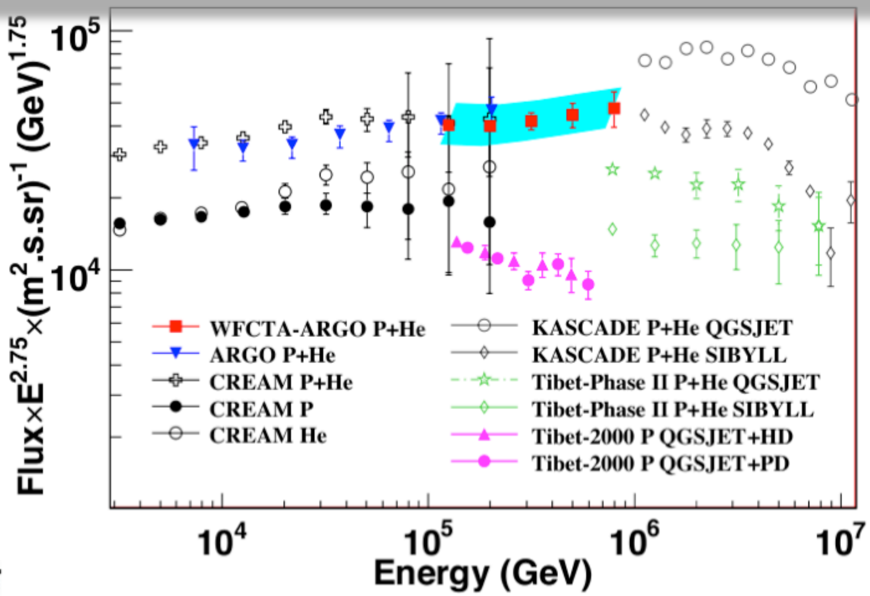




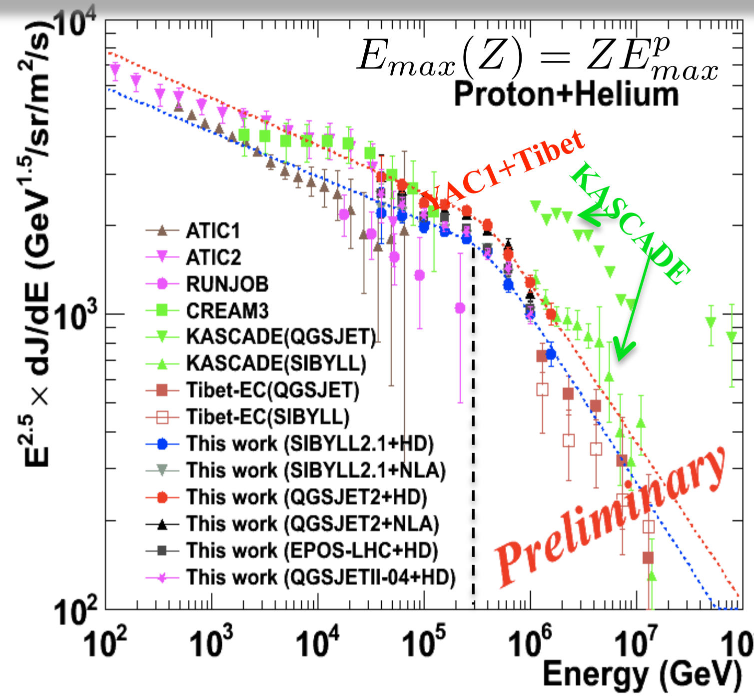


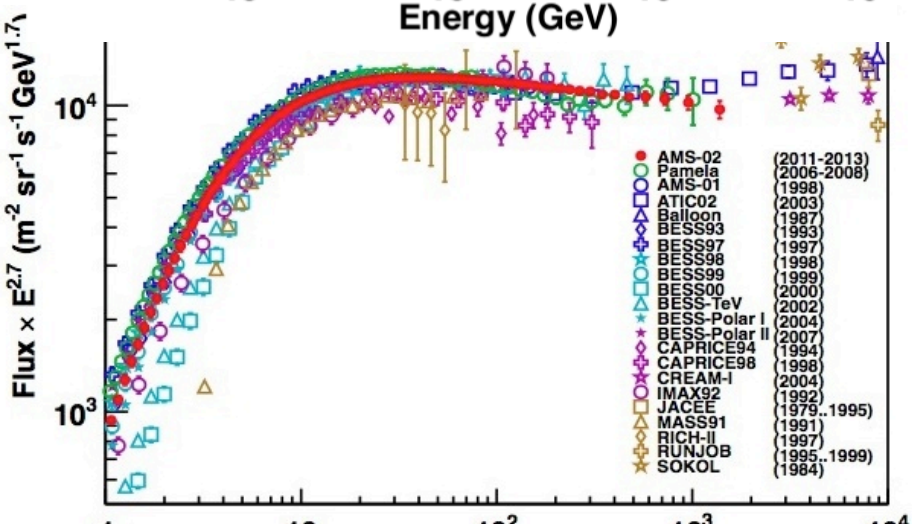
Some questions on CR

✓ Injection power law and relative abundances p,He



✓ Uncertainty in the knee position of p and He



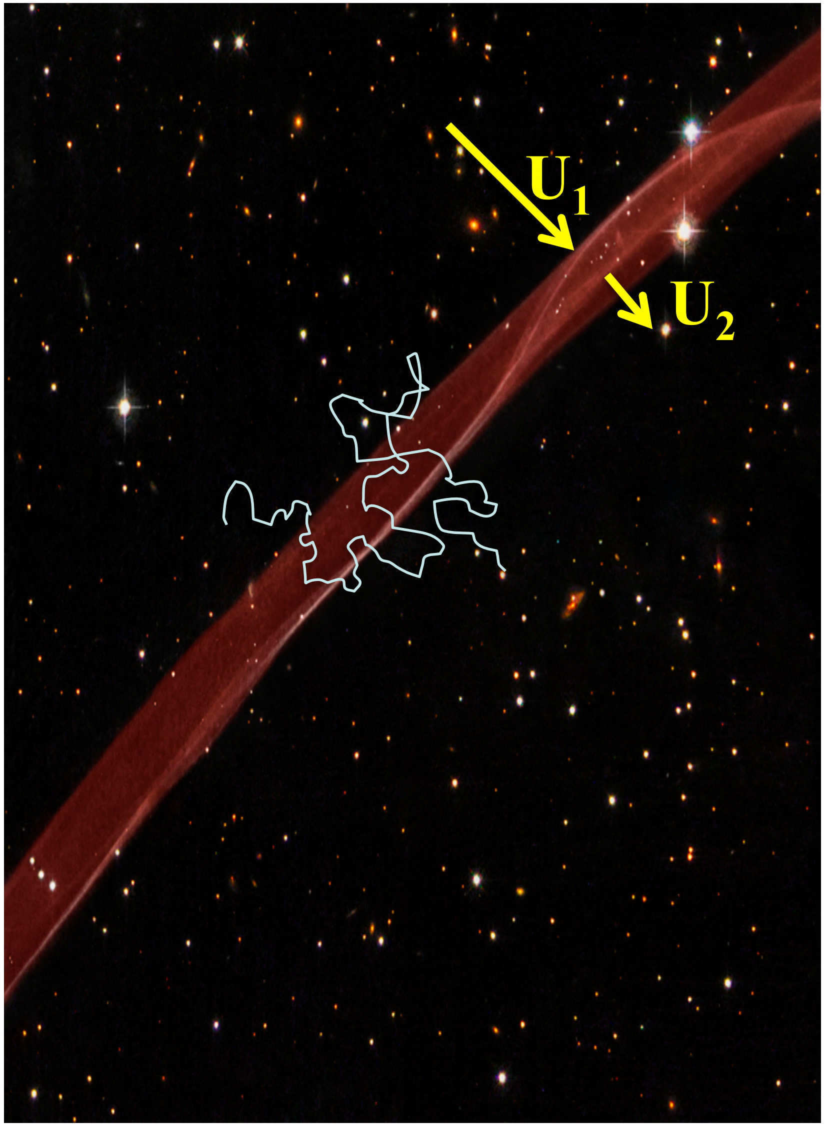


✓ Presence of spectral brakes

✓ Hadronic interaction models in ground based experiments seem the largest source of uncertainty.

✓ Gamma rays observations could give important insights on the details of acceleration (spectrum & maximum energy) and propagation.

Diffusive Shock Acceleration



$$V_s = 10^4 E_{51}^{1/2} M_{ej}^{-1/2} km/s$$

- Diffusion of charged particles back and forth through the shock leads to
$$\frac{\Delta E}{E} = \frac{4}{3}(U_1 - U_2)$$
- Particles are accelerated to a power law spectrum $Q(E) \propto E^{-\gamma}$
- The slope of the spectrum depends only on the shock compression factor, in the case of strong shock (M>>1) $Q \sim E^{-2}$.
- The maximum acceleration energy depends only on the diffusion in the shock region

Note: the efficiency required (~10% of the SNR energy) signals the **need for a non linear theory of the acceleration process**, that takes into account the effect of CR on the shock itself

Maximum Acceleration Energy

Maximum acceleration energy can be determined comparing the residence time of CR in the acceleration region with the relevant time scales of the problem

$$\tau_{diff} = \frac{D(E)}{V_{sh}^2} \leq \mathrm{Min}(\tau_{SNR}, \tau_{loss}, \tau_{esc})$$

using a typical value $V_{sH}\sim10^4$ km/s and the diffusion coefficient in the ISM derived from B/C ratio $D(E)\sim10^{29}$ cm^2/s one gets a maximum energy at GeV level

Need for additional turbulence: the effect of CR themselves produces an amplification of the turbulent magnetic field locally at the acceleration region (Lagagge and Cesarsky 1983)

$$D(E) = \frac{1}{3} r_L(E) v \frac{1}{\mathcal{F}_0(k(E))} \qquad \mathcal{F}_0(k) = \frac{kP(k)}{B_0^2/8\pi}$$

ratio of the energy density of the turbulent field with the background B_0

- ✓ **SN in ISM medium**: $E_{max}\sim2\mathrm{x}10^5$ GeV, weakly dependent on the parameters (factor of ten difficult to recover)
- ✓ **SN in a supergiant wind**: $E_{max} \sim 2\mathrm{x}10^6$ GeV, almost the right value for protons knee

Magnetic field amplification

From the observational point of view the best evidence of magnetic field amplification comes from the X-rays observations

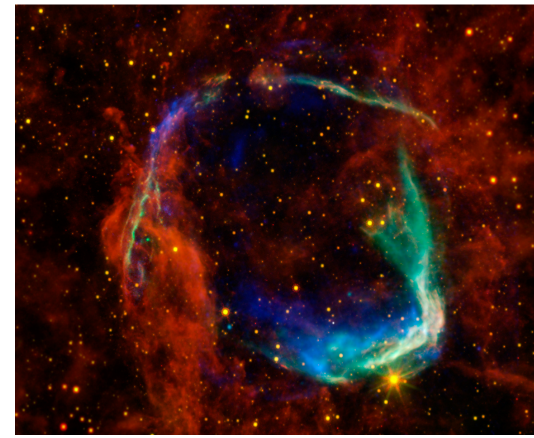
Typical size of the observed filaments ~ 10^{-2} parsec

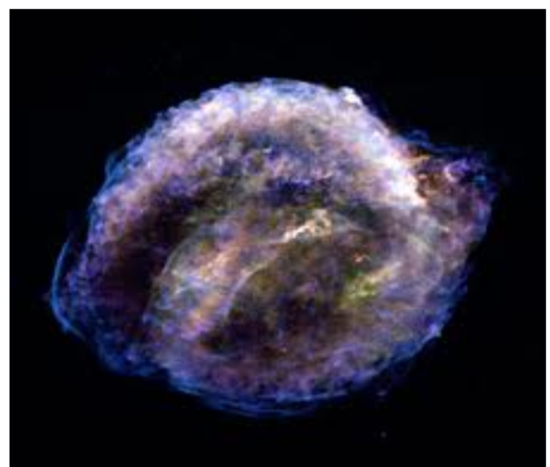
The emission in filaments is non-thermal, due to synchrotron of the highest energy electrons in the accelerator

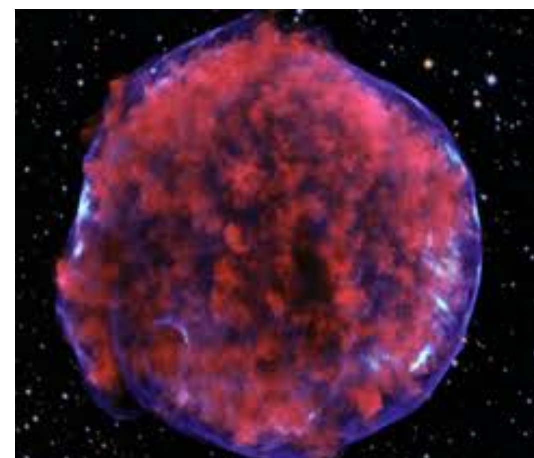
$$\Delta x \approx \sqrt{D(E_{max})\tau_{loss}(E_{max})} \approx 0.04\ B_{100}^{-3/2}\ \mathrm{pc}$$

Comparison with the observed thickness leads to an estimate for the local field

$$B \simeq 100\mu G$$



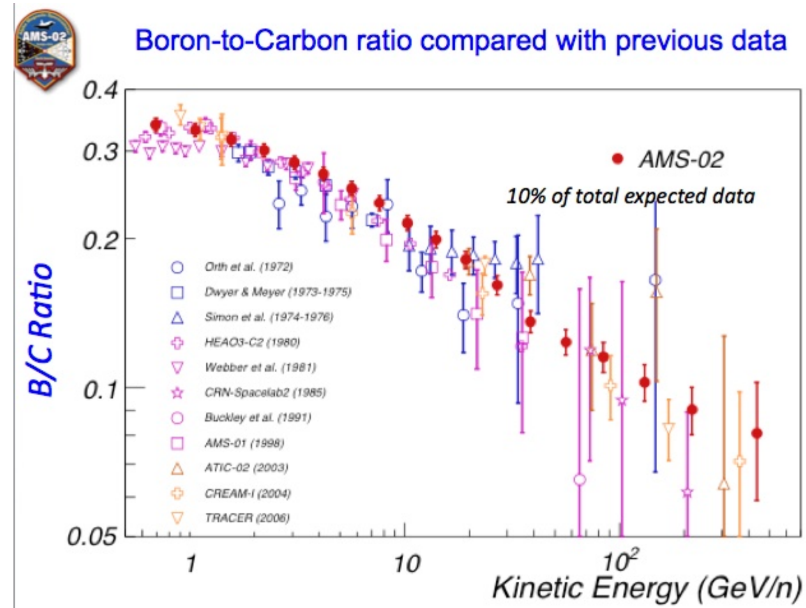




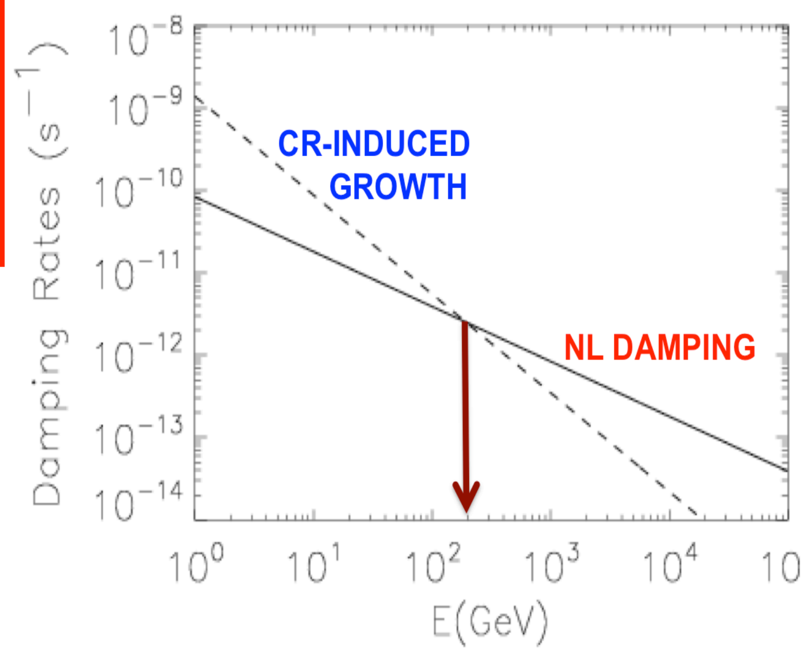
CR Propagation and self generated turbulence

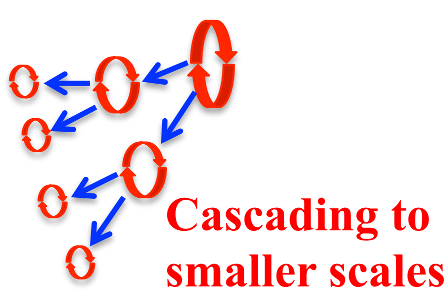
The decrease of B/C with energy/nucleon is the best sign of a rigidity dependent grammage traversed by CR on their way out of the galaxy. It confirms the picture of a diffusive propagation of CR

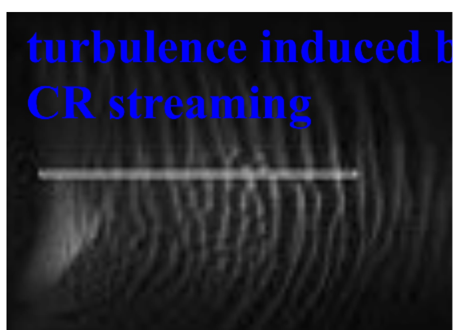
$$\frac{\Phi_B(E)}{\Phi_C(E)} \propto X(E) \propto \frac{1}{D(E)} \propto E^{-\delta}$$



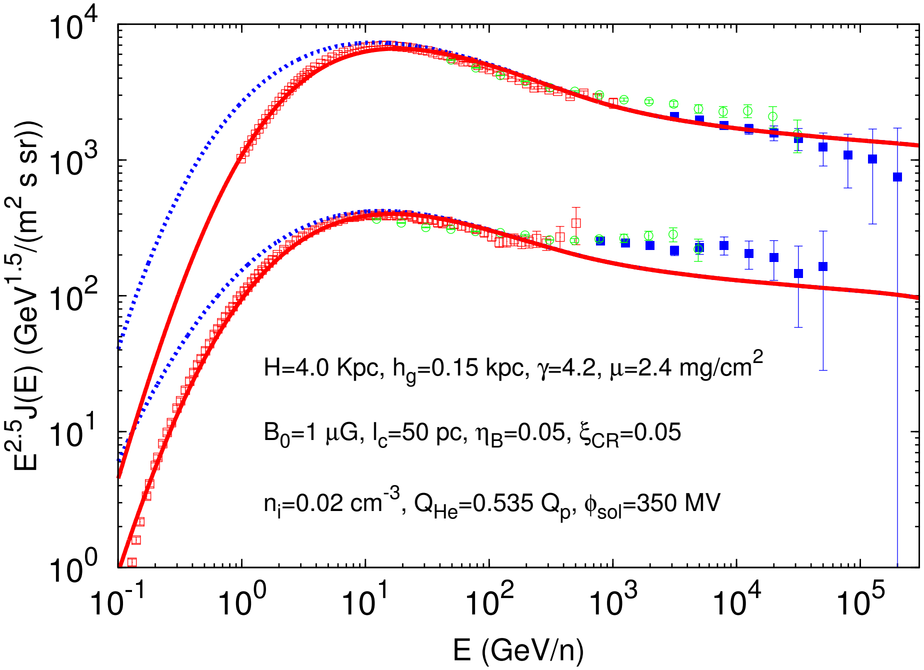
CR may excite a streaming instability when their motion is super-alfvenic. Self generated turbulence together with pre-existing one, injected by SN and cascading to smaller scales, produces the conditions for CR diffusion in a non-linear self regulating way.





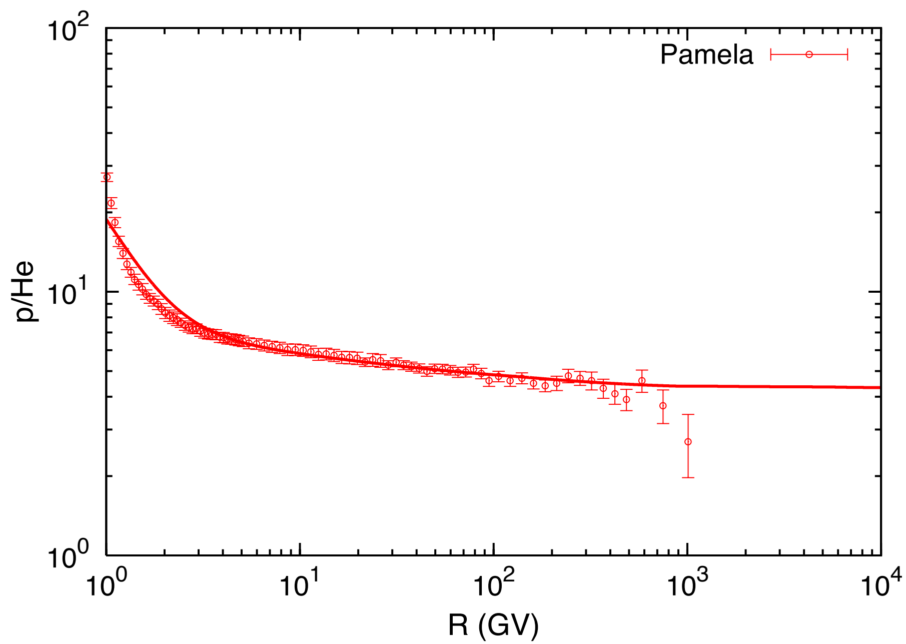


CR fluxes



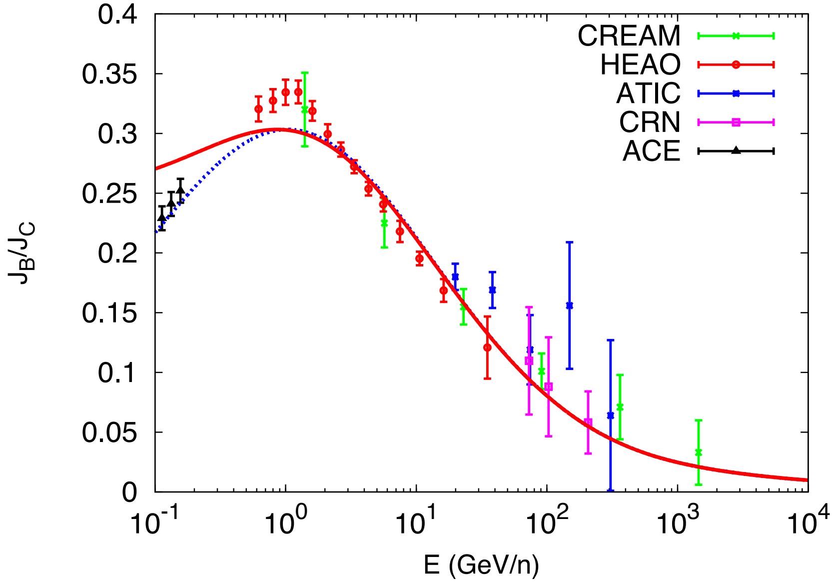
- ✓ Proton spectrum is in excellent agreement with Pamela and CREAM data, with a clear hardening effect around 200 GeV/n.
- ✓ At high energy He spectrum shows a poorer agreement with CREAM data, still inside a 20% systematic error in the energy determination.

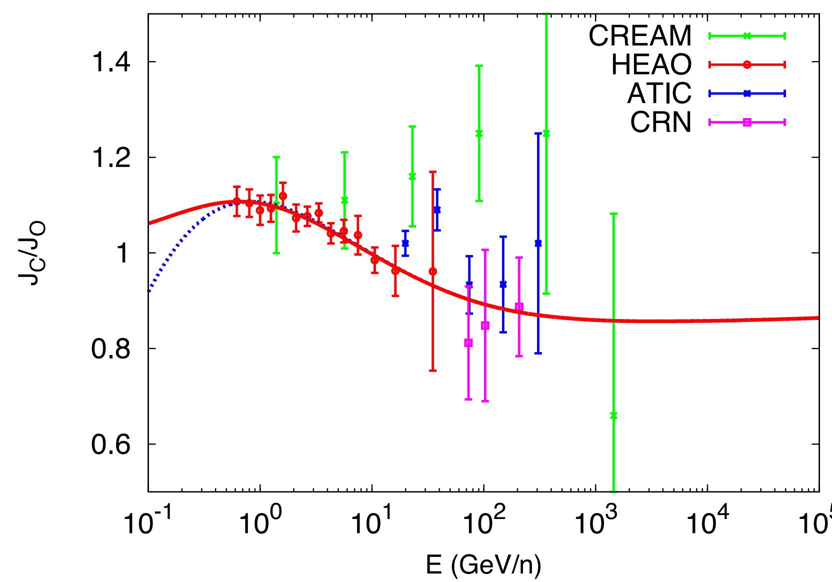
- ✓ The observed ratio p/He is reproduced fairly well. Other models, based on both simple diffusion or reacceleration, do not show the same agreement in the whole observed energy range.

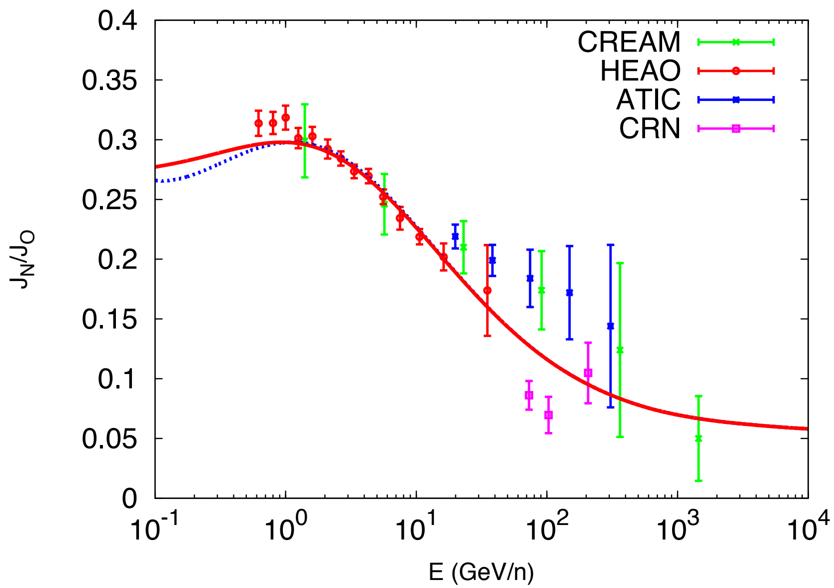


RA & Blasi 2013

Fluxes ratios







RA & Blasi 2013

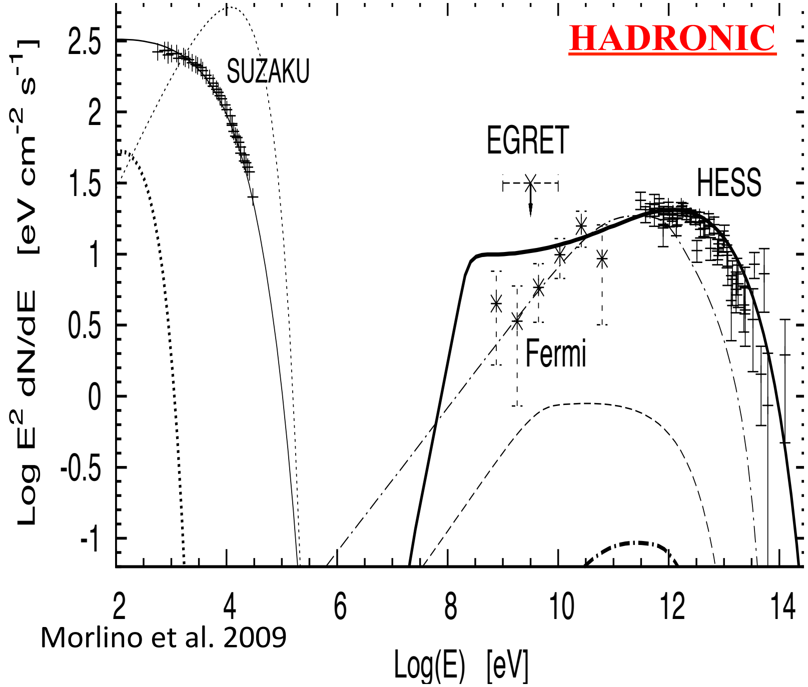
- ✓ The ratios of primary/secondary and primary/primary obtained self consistently reproduce quite well experimental observations.
- ✓ No need for artificial breaks in the injection spectrum and/or diffusion coefficient, as in the case of simple diffusion models or models with second order Fermi re-acceleration.

γ ray emission and galactic CR

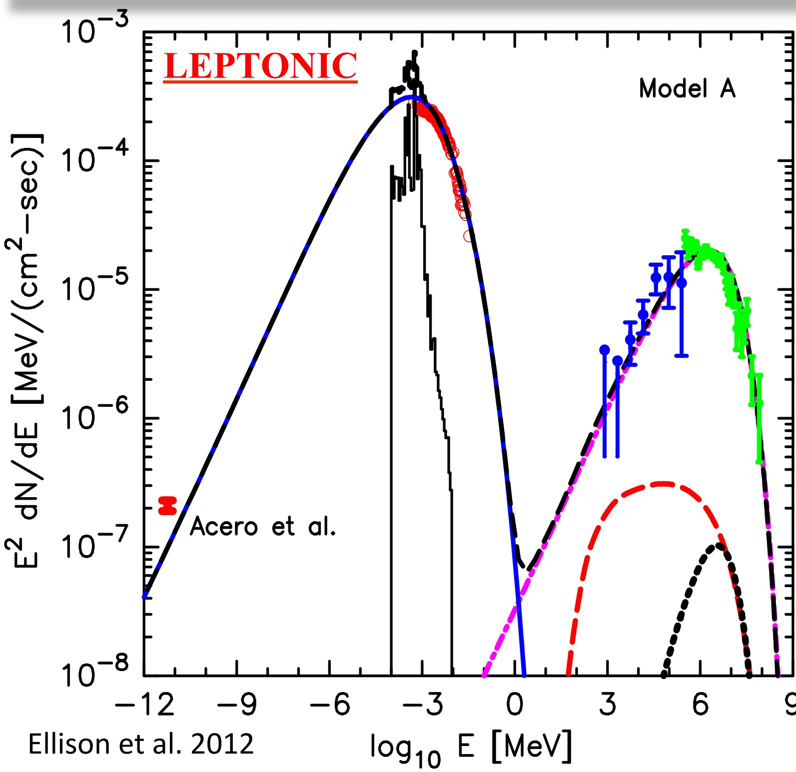
- The best change of testing the acceleration models of CR in SNRs is in modeling the multi-frequency emission and its morphology of selected SNRs.
- I will discuss two cases of SNRs that are sufficiently isolated to be modeled as individual sources, using them to illustrate the type of information we can gather from observations in gamma rays.
- Note that emissions from the acceleration site bring information about the acceleration spectrum, which is typically different from the spectrum that leaves the accelerator being injected in the ISM.
- The spectrum injected in the ISM by the source can be tested observing the gamma ray emission from molecular clouds nearby the SNR. I will also address this point discussing two different scenarios in the interplay between SNR and cloud.
- γ-rays produced by CR propagation in the galaxy give rise to the diffuse gamma background of the galactic halo, it can be used to test propagation models.

The case of RXJ1713

- observed in keV, GeV and TeV range
  Bamba et al. (2009); Aharonian et al. (2004-2007); Abdo et al. (2011)
- an hadronic origin of GeV-TeV emissions would easily account for X-ray rims observed (B~160 μG)
- no thermal X-rays: electrons not in thermal equilibrium with protons (fast shock)



Morlino et al. 2009

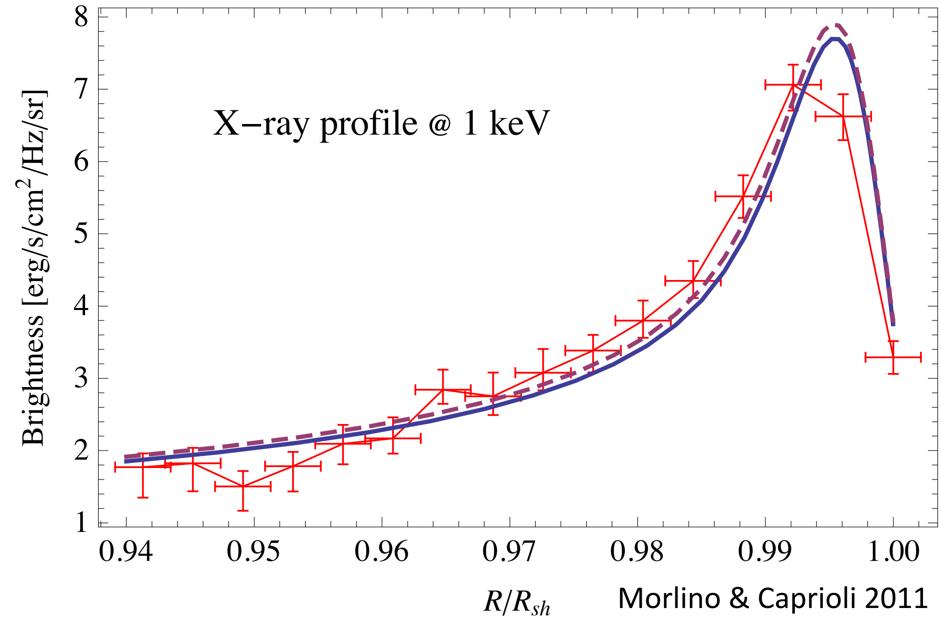


Ellison et al. 2012

- a very slow rate of Coulomb interactions heats electrons at ~1 keV. No oxygen lines observed, very small densities, not efficient pp interactions.
- leptonic origin of GeV-TeV emissions requires high IR light (~20 times than observed) and too low B (if compared to X-ray emission).
- complex environment, future high resolution gamma ray observations will distinguish different emitting regions.

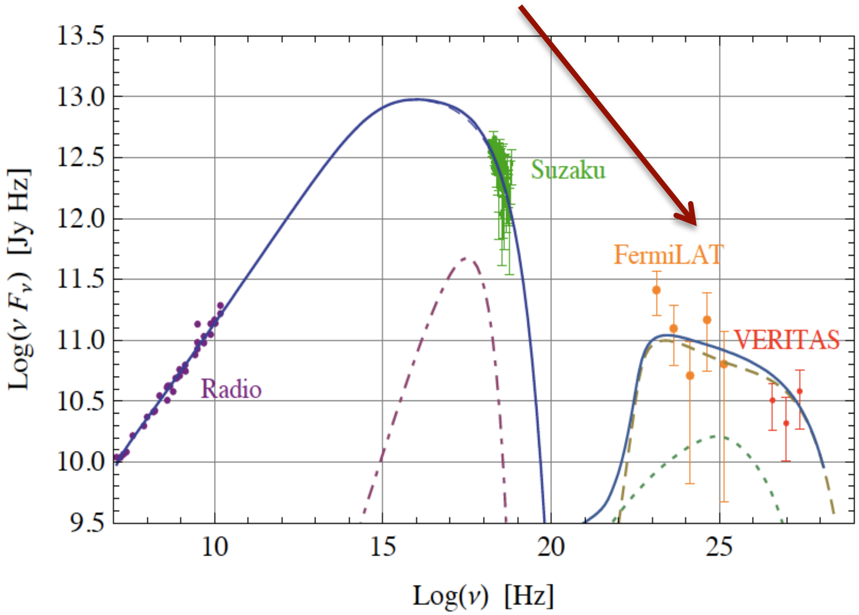
The case of Tycho

- ✓ SNIa exploded in roughly homogeneous ISM (regular spherical shape)
- ✓ From X-ray observations B~300 μG
- ✓ Maximum energy protons E_{max}~500 TeV



Morlino & Caprioli 2011

Steep spectrum hard to explain with leptons



Morlino & Caprioli 2011

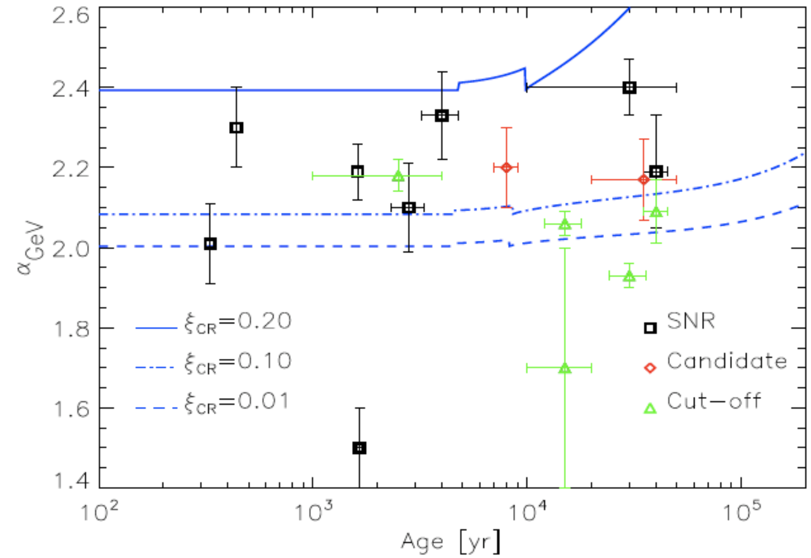
- ✓ steep spectrum as a result of finite velocity of the scattering centers (Caprioli et al. 2010, Ptuskin et al. 2010, Morlino & Caprioli 2011)
- ✓ steep spectrum as a result of medium characteristics (inhomogeneity) (Berezhko et al. 2013)
- ✓ Important example of the credibility level of theories based on NLDSA. Space resolved gamma ray observations would test different theoretical hypothesis

γ rays from isolated SNR – quick summary

Problematic spectra

The non linear theory of DSA (as well as the test particle theory) all predict CR spectra close to E^{-2} and even harder than E^{-2} at E>100 GeV. Possible issue if compared with

- ✓ gamma ray spectra from selected SNR
- ✓ CR anisotropy (requires $D(E) \sim E^{0.75}$), may be ameliorated by the effect of self induced turbulence

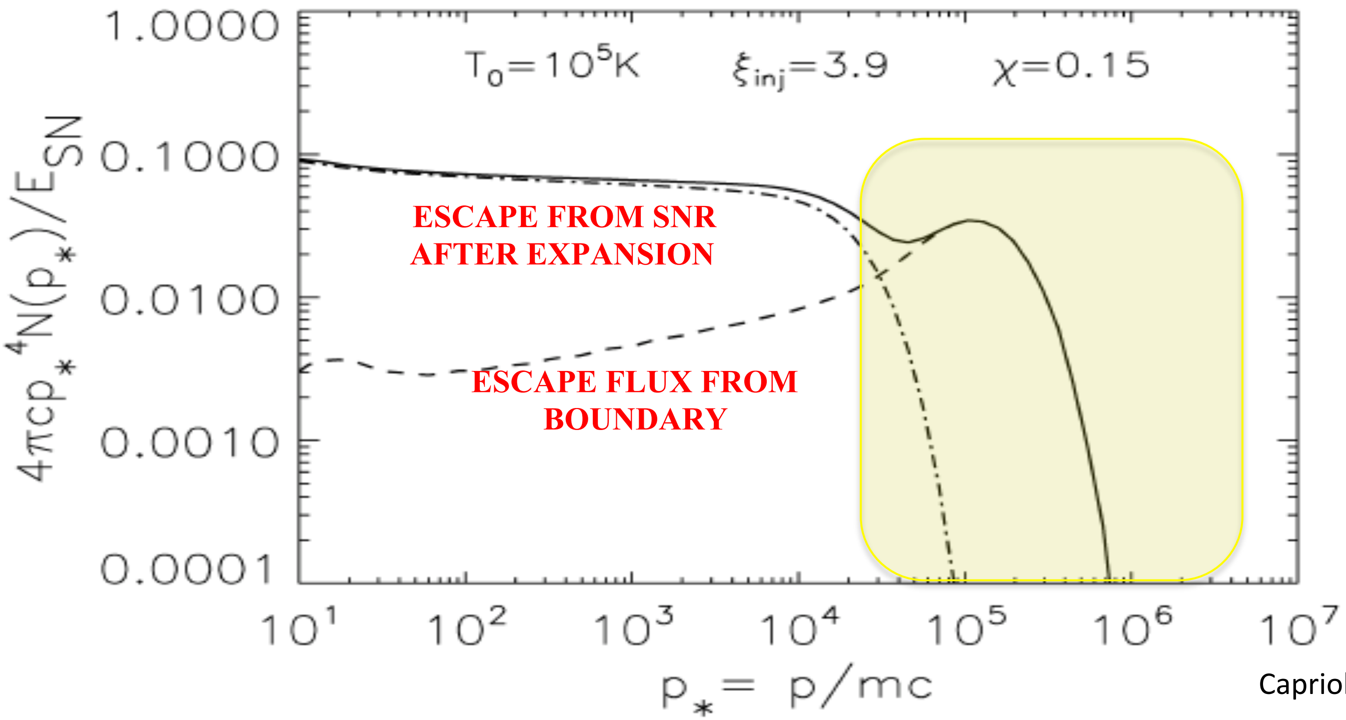


Caprioli et al. 2011

- ✓ The pion peak has not been seen so far (only in molecular clouds this feature seems observed, see later)
- ✓ The discrimination between leptonic models (ICS) and hadronic models (π^0 decay) can be achieved just observing the spectrum only with high angular resolution. Different parts of the SNR may have different spectra reflecting a different origin or/and the presence/absence of nearby targets (molecular clouds, see later). This may be the case of RXJ1713.
- ✓ Extension of the observations to high energies can provide an evidence of a cut-off in the PeV region (but low probability of finding a suitable SNR for this observations).

Escape of CR from accelerator

Escape is the physical phenomenon that transforms accelerated particles into CR.



Caprioli et al. 2009

CR injected in the ISM are the superposition of

✓ particles escaped during the Sedov-Taylor phase (emission peaked on p_{max})

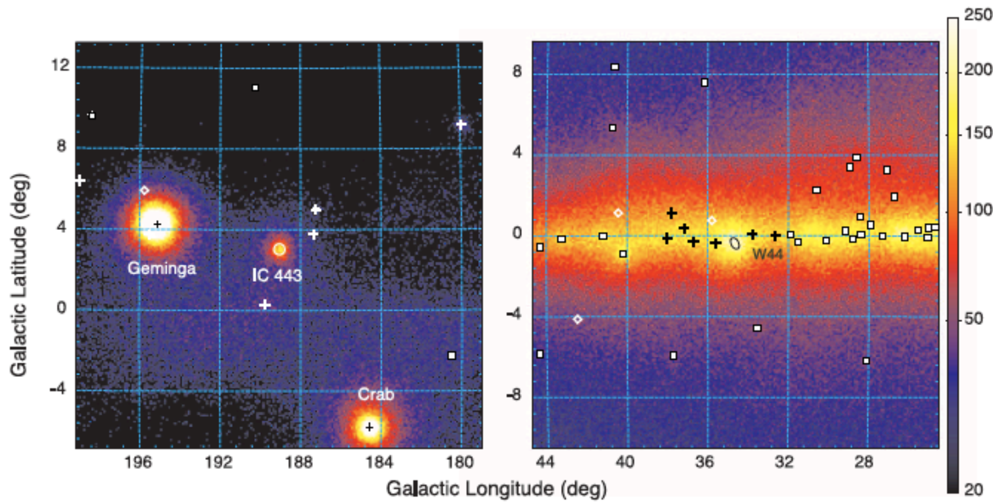
✓ particles released in the ISM after expansion

γ ray emission from molecular clouds

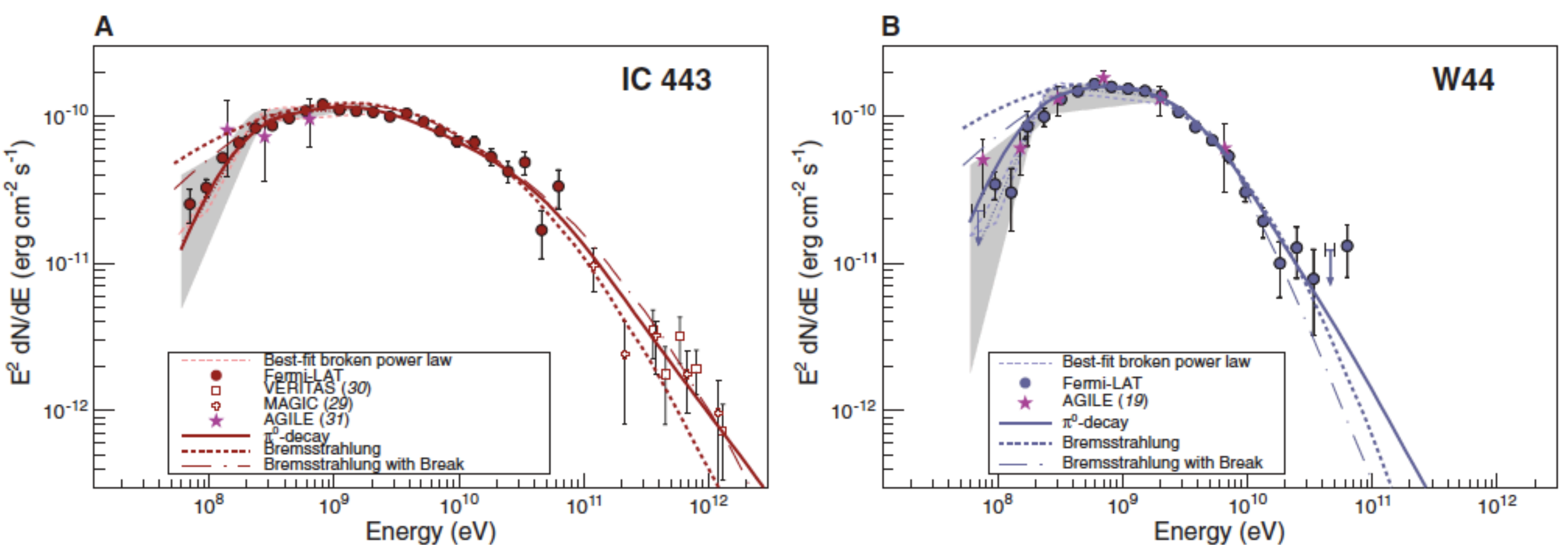
- ✓ Firm observation of the pion bump

$$pp \to \pi^0 \to \gamma\gamma$$

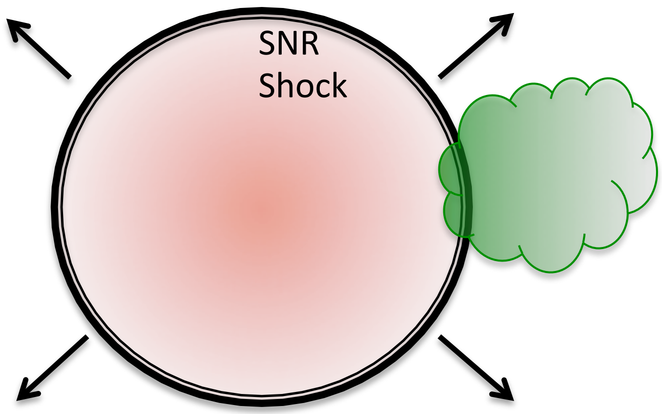
- ✓ SN close to molecular clouds are very interesting laboratories to investigate CR propagation around sources and escape from sources.



Ackermann et al. 2013



Shock inside the cloud

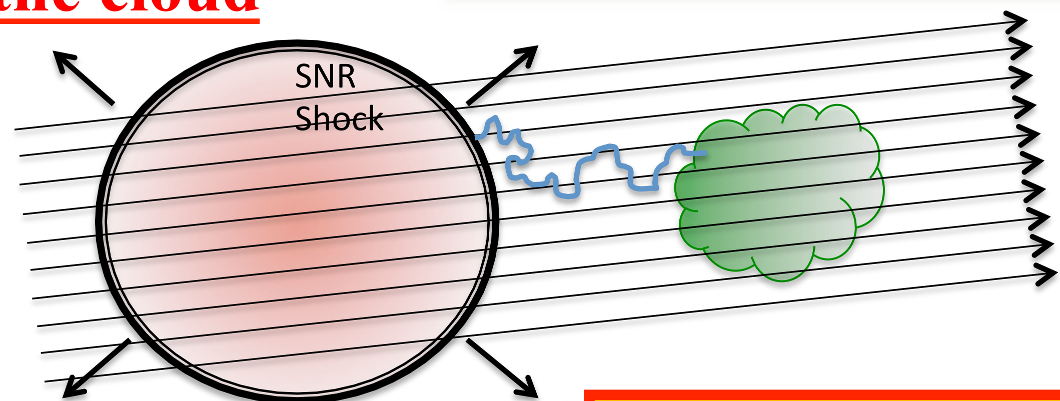


- the shock becomes collisional on scales

$$\lambda \approx \frac{1}{n_{cloud}\sigma_{mol}} \sim 10^{10} \left(\frac{n_{cloud}}{10^4 cm^{-3}}\right)^{-1} \left(\frac{\sigma_{mol}}{10^{-14} cm^2}\right)^{-1} cm$$

- It slows down since it feels the matter in the cloud, particle already accelerated escape streaming away and interacting with matter in the molecular cloud.

Shock outside the cloud



- the spectrum of particles that reaches the cloud has a low energy cut-off time dependent

$$n(E) = n_s(E) \exp\left[-\frac{r^2}{4D(E)T}\right]$$

- γ-rays produced by CR with $E>E_{min}$ reproduce the CR spectrum

- γ-rays emission in this case could give direct information on the escaped flux of CR.

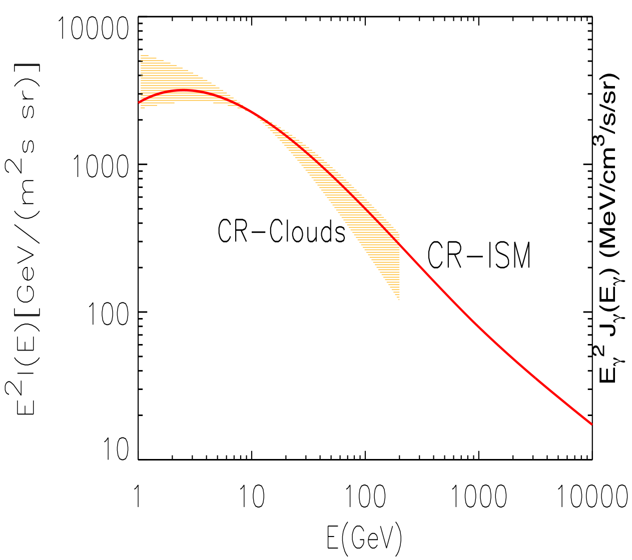
γ rays from molecular clouds – quick summary

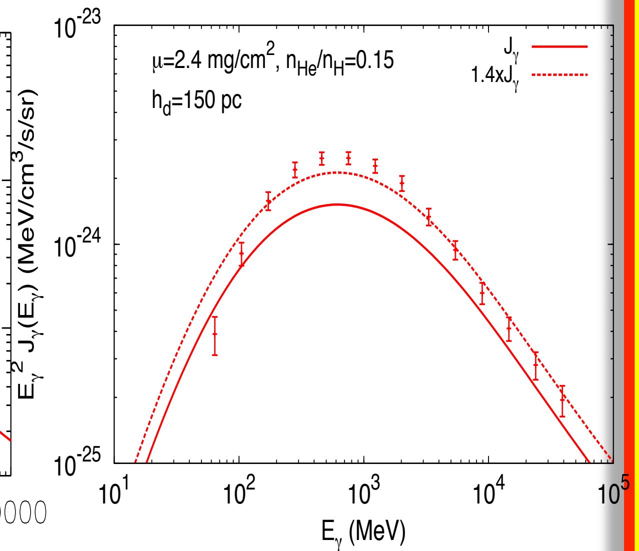
- ✓ Escape is the weak link between acceleration and CR observed on earth. High energy particles injected by the source are the sum of “escaped” and “released” particles.

- ✓ The two contributions to the injected spectrum (i.e. from escaped particles and particles released after the end of expansion) can be disentangled looking at the gamma ray emission from clouds.

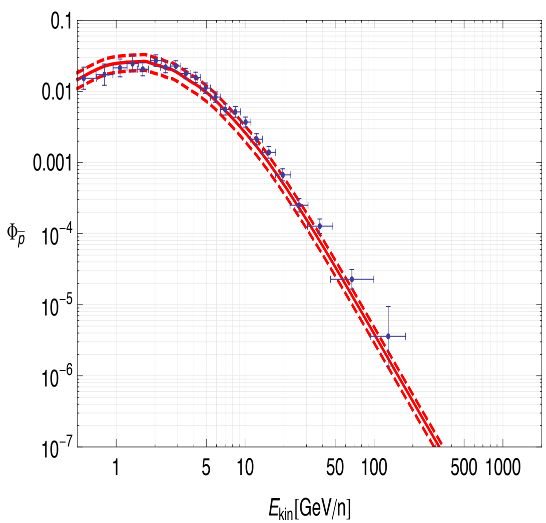
- ✓ The study of these emissions can also give important insights on the CR propagation inside clouds, most likely on self-generated turbulence, and on the diffusion topology.

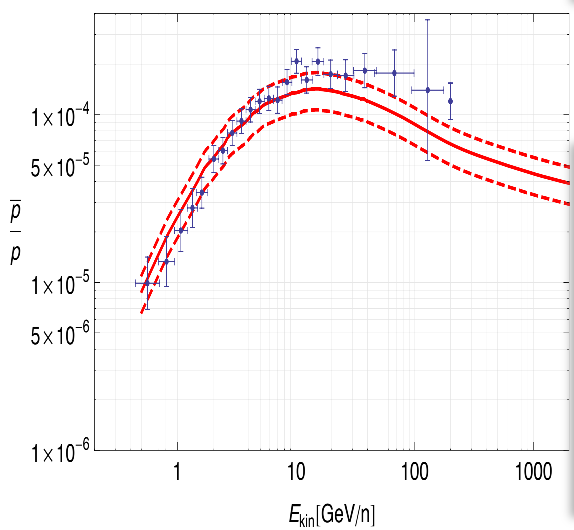
Diffuse gamma rays & antiprotons





- ✓ The proton spectrum in the ISM compare well with the flux inferred from gamma ray observations of clouds in the Gould's belt.
- ✓ The galactic gamma ray emissivity is well reproduced in shape and within 40% accuracy in normalization (geometrical factor).

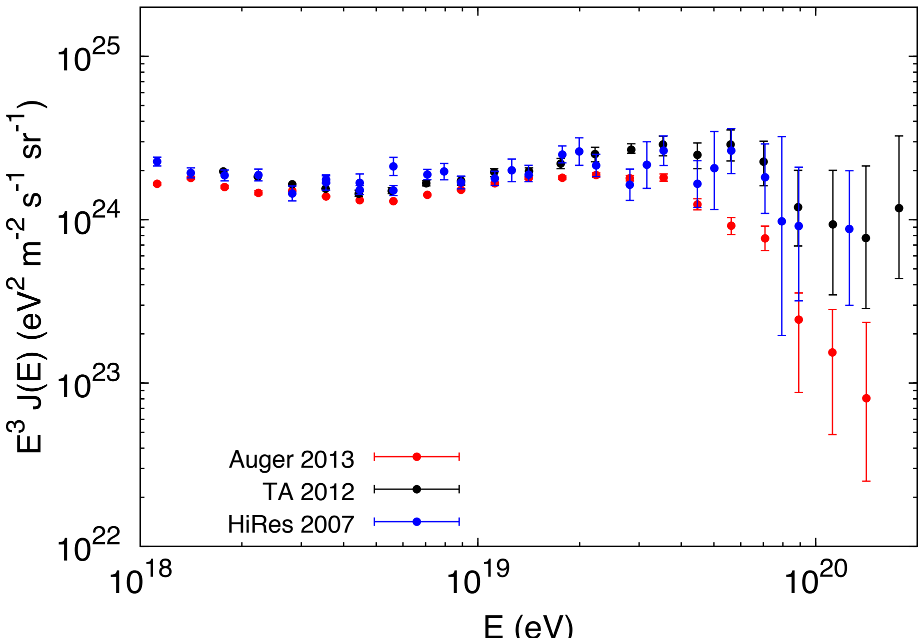




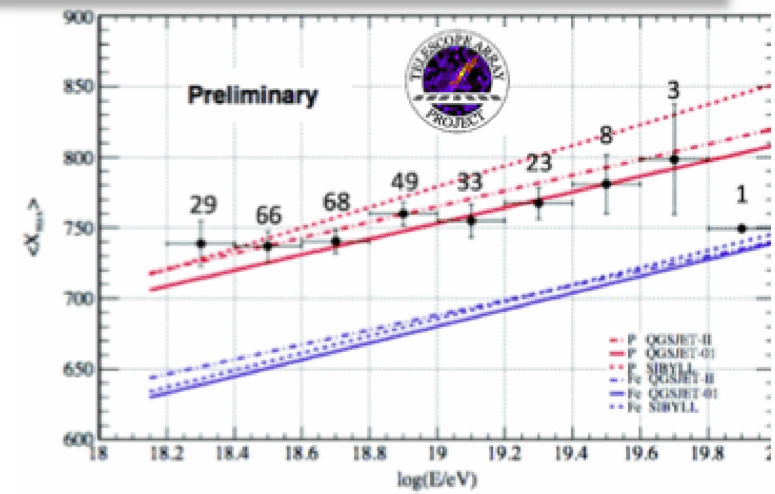
- ✓ Given the uncertainties on the anti-proton cross section production, the observed anti-proton flux is very well reproduced.

RA, Blasi, Serpico (in preparation)

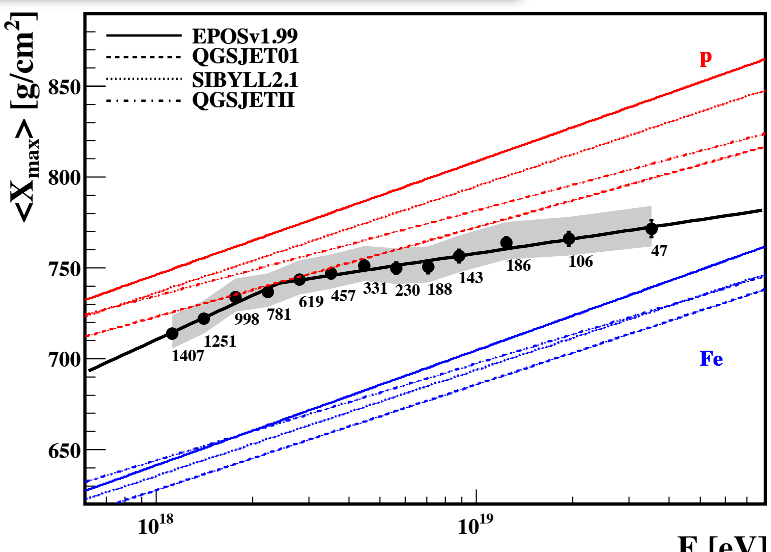
CR at Ultra High Energies

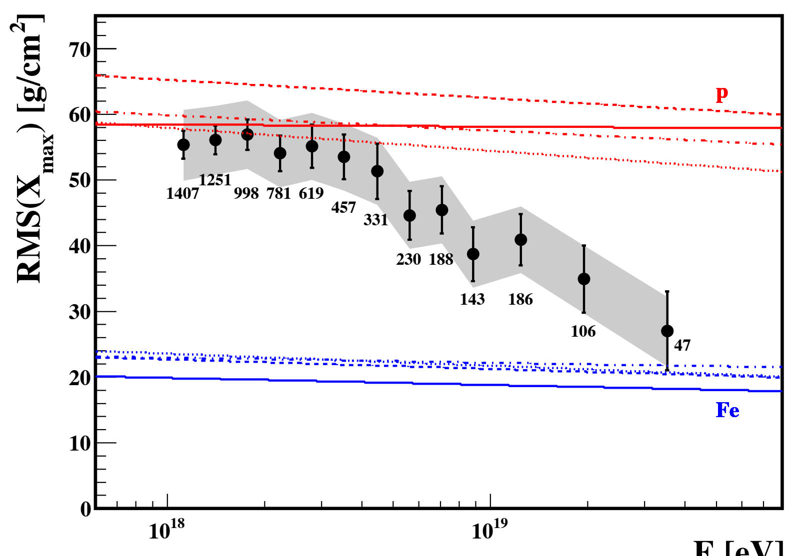


✓ HiRes-TA points toward a pure proton composition at all energies.



✓ Auger observes an increasing heavy composition at the highest energies

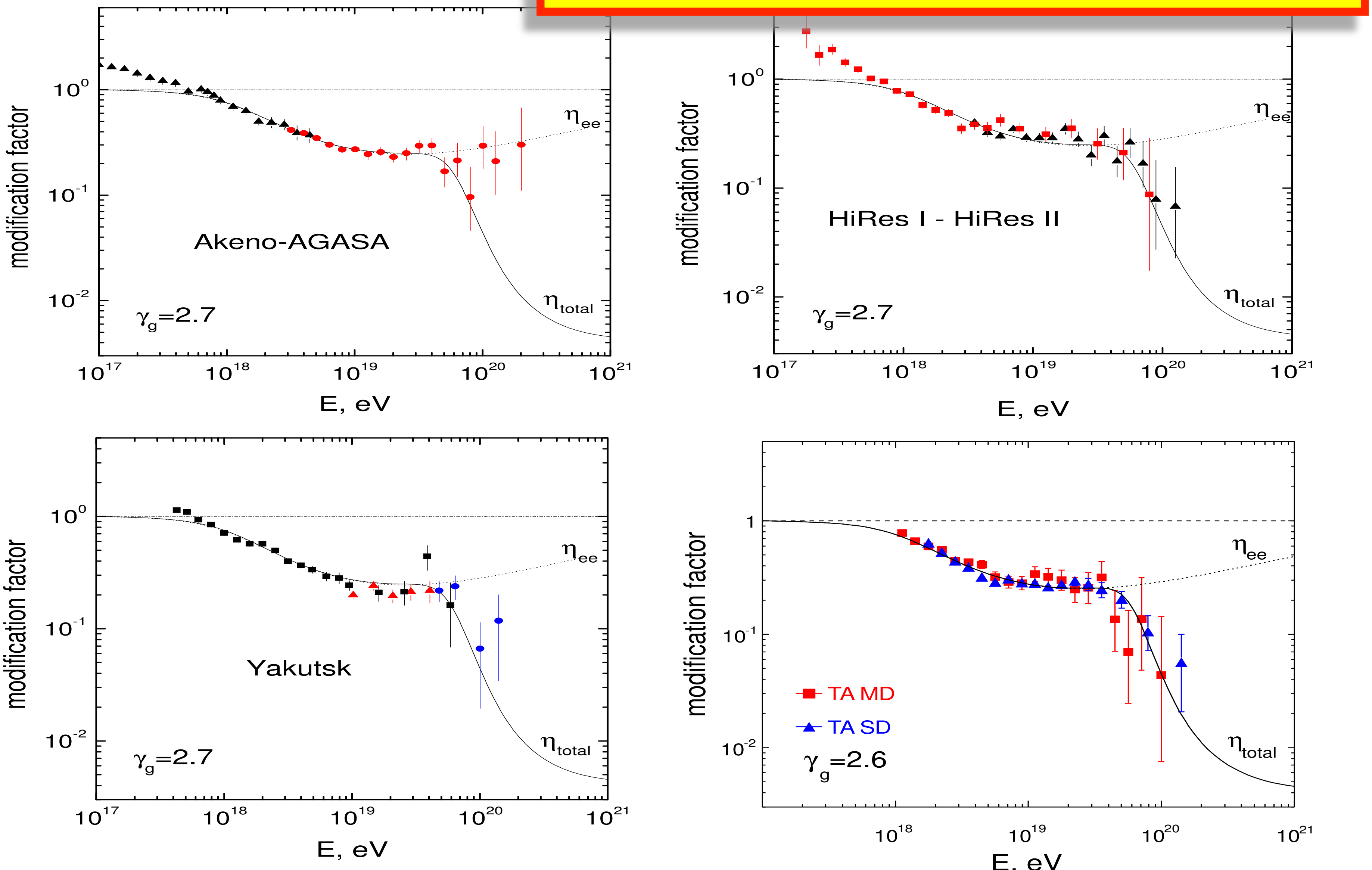




Dip Model

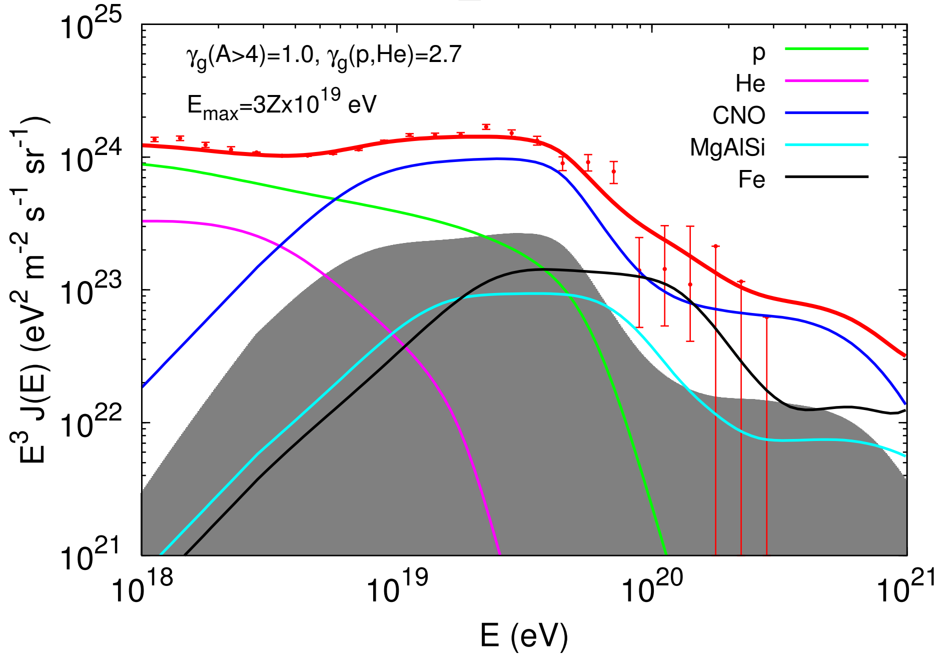
the protons footprint

In the energy range 10^{18} - 5×10^{19} eV the spectrum behavior is a signature of the pair production process of UHE protons on the CMB radiation field.



Berezinsky et al (2002) - RA et al. (2007-2012)

Mixed Composition



Two types of extra-galactic sources:

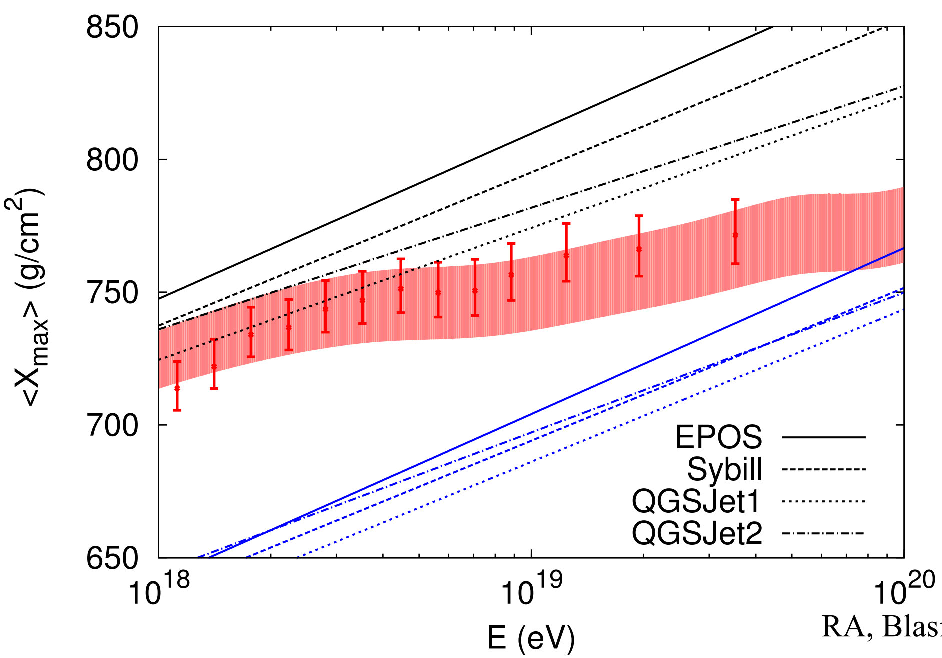
- ✓ light component steep injection (γ_g>2.5)

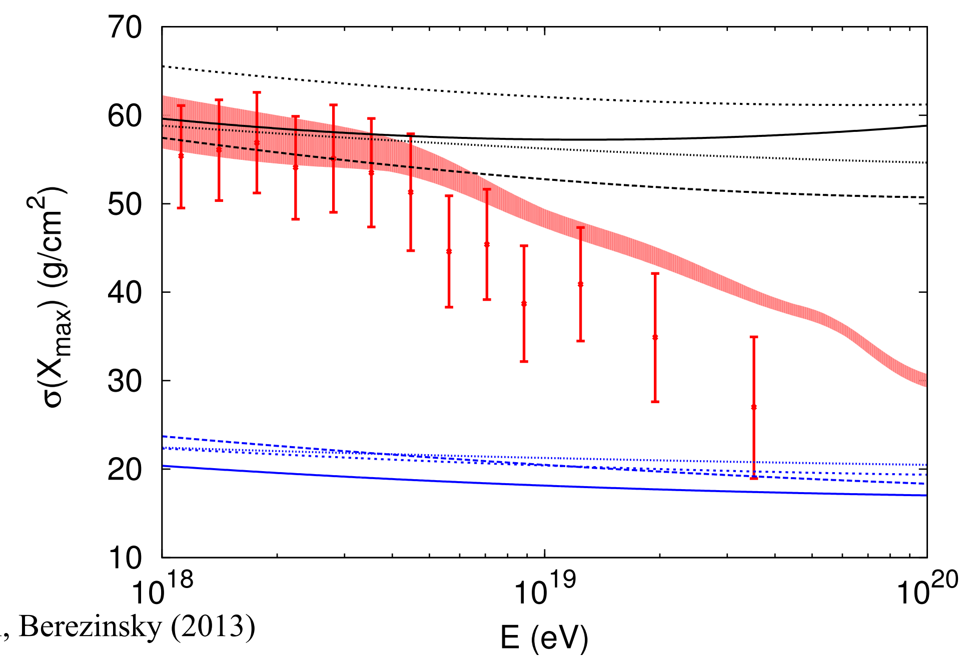
$$\mathcal{L}_0 = n_{UHE} L_{UHE} \simeq 10^{47} \frac{\text{erg}}{\text{Mpc}^3\text{y}}$$

- ✓ heavy component flat injection (γ_g<1.5)

$$\mathcal{L}_0 = n_{UHE} L_{UHE} \simeq 10^{44} \frac{\text{erg}}{\text{Mpc}^3\text{y}}$$

- ✓ Maximum energy E_{max} < few 10^{19} eV



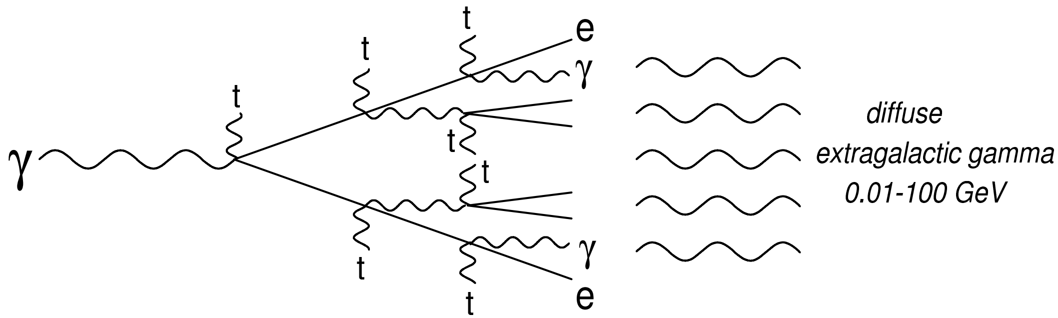


RA, Blasi, Berezinsky (2013)

Production of secondary γ ν

Cascade upper limit

$p\gamma \to e^{\pm}$
$p\gamma \to \pi^0 \to \gamma$
$p\gamma \to \pi^{\pm} \to e^{\pm}, \nu$

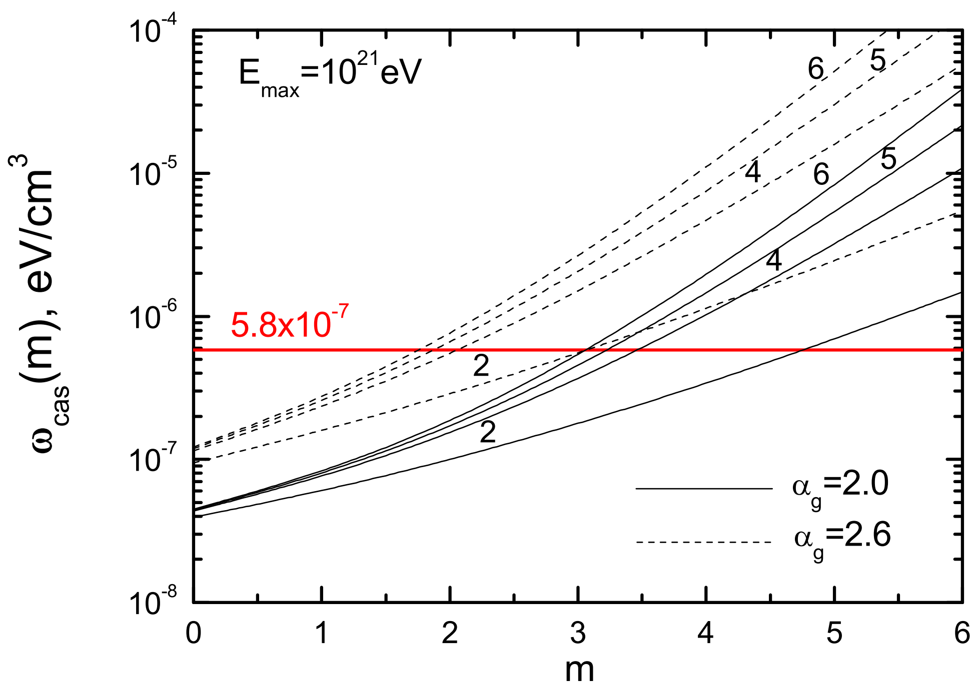


$$\omega_{cas}^{max} > \omega_{cas}^{\pi} > \frac{4\pi}{c}\int_E^{\infty} E' J_\nu(E')dE' > \frac{4\pi}{c}E_\nu J_\nu(> E)$$

Fermi-LAT data
$\omega_{cas} = 5.8 \times 10^{-7}$ eV/cm^3

Assuming an E^{-2} neutrino flux , the cascade limit can be expressed in terms of the energy densities of photons and e^+e^- initiated cascades

$$E^2 J_\nu(E) \leq \frac{c}{4\pi}\frac{\omega_{cas}^{max}}{\ln(E_{max}/E_{min})}\frac{1}{1+\omega_{cas}^{e^+e^-}/\omega_{cas}^{\pi}}$$



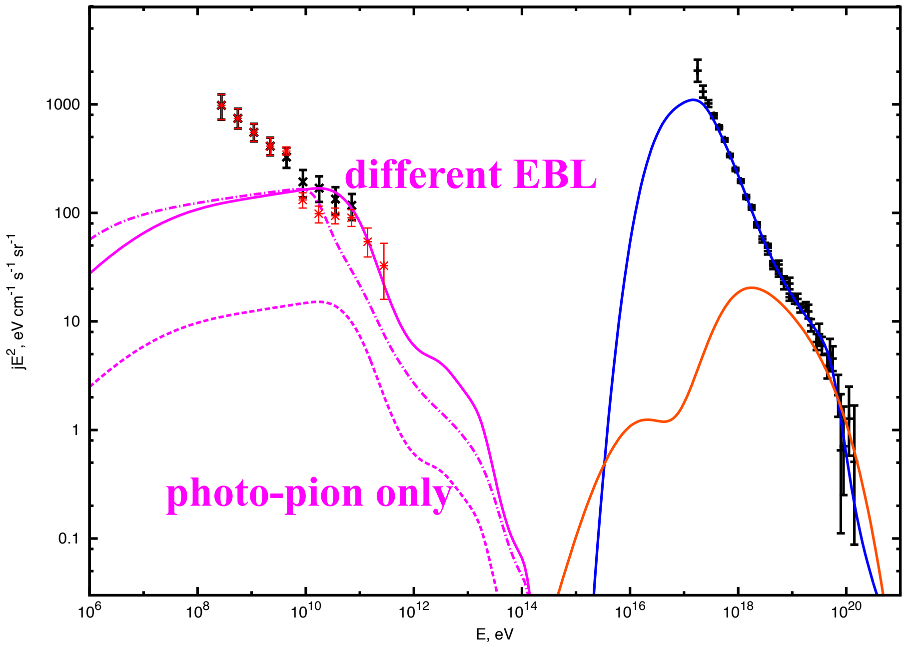
Berezinsky, Gazizov, Kachelriess, Ostapchenko (2011)

The cascade upper limit constrains the source parameters: cosmological evolution, injection power law and maximum acceleration energy.

$$Q(E) = Q_0(1+z)^m\left(\frac{E}{E_0}\right)^{\alpha_g} e^{-E/E_{max}}$$

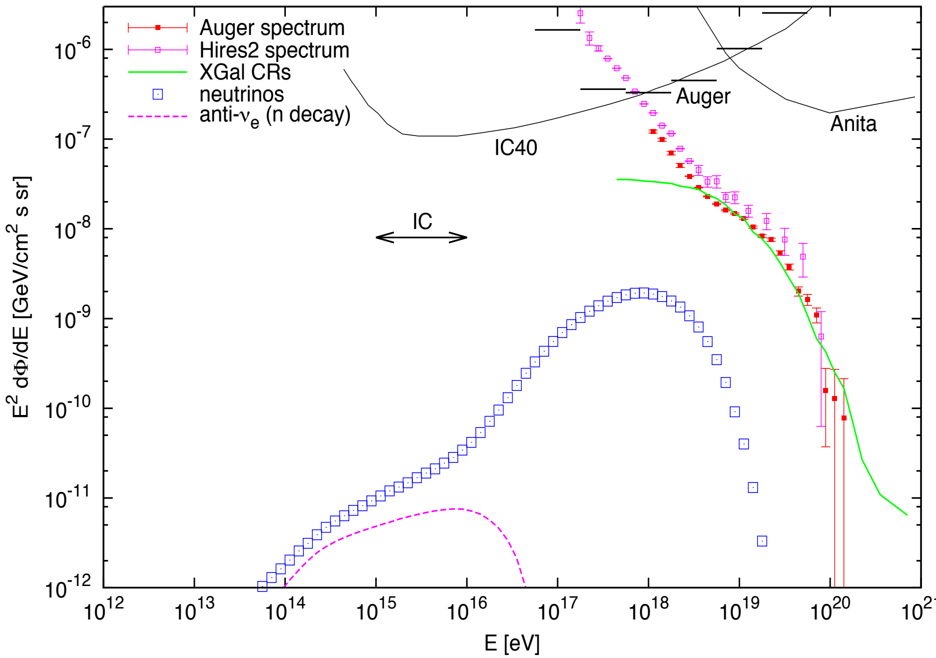
γ- diffuse spectra

Dip Model



Gelmini, Kalashev, Semikoz (2012)

Mixed Composition Model



Roulet, Sigl, van Vliet, Mollerach (2013)

γ,ν from UHE protons

- ✓ at $E>10^{17}$ eV dominant interaction on CMB background
- ✓ gamma flux from pair production
- ✓ Fermi-LAT observations constrain neutrino fluxes (cosmological evolution, maximum acceleration energy).

γ,ν from UHE nuclei

UHE nuclei suffer photo-pion production on CMB only for energies above AE_{GZK}. The production of gamma and neutrino strongly depends on the nuclei maximum energy. UHE neutrino production practically disappears in models with maximum nuclei acceleration energy $E_{max} < 10^{21}$ eV.

γ from distant AGN

The observed high energy gamma ray signal by distant blazars may be dominated by secondary gamma rays produced along the line of sight by the interaction of UHE protons with background photons. This hypothesis solves the problems connected with the flux observed by too distant AGN.

$$J_{\gamma,primary} \propto \frac{1}{d^2} exp^{-d/\lambda_\gamma}$$

$$J_{\gamma,secondary} \propto \frac{p\lambda_\gamma}{4\pi d^2}\left[1 - e^{-d/\lambda_\gamma}\right]$$

at large distances the contribution of secondaries dominates.

$$\Delta\theta \simeq 0.1^\circ \left(\frac{B}{10^{-14}G}\right)\left(\frac{4\times 10^7 GeV}{E}\right)\left(\frac{D}{1Gpc}\right)\left(\frac{l_c}{1Mpc}\right)$$

$$\Delta t \simeq 10^4 y \left(\frac{B}{10^{-14}G}\right)^2\left(\frac{10^7 GeV}{E}\right)^2\left(\frac{D}{1Gpc}\right)^2\left(\frac{l_c}{1Mpc}\right)$$

this model requires low IMF at the level of femtogaus.

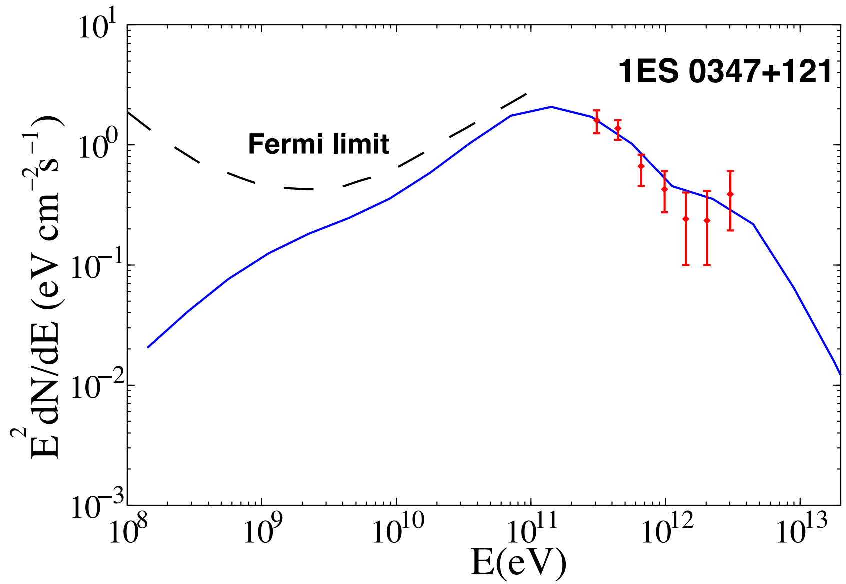
The spectrum of the final cascade is universal. The EM cascade behaves as a sort of calorimeter that redistribute the initial energy into gamma rays (and neutrinos) with a given spectrum.

Ferrigno, Blasi, De Marco (2004) Essey, Kalashev, Kusenko, Beacom (2009-13)

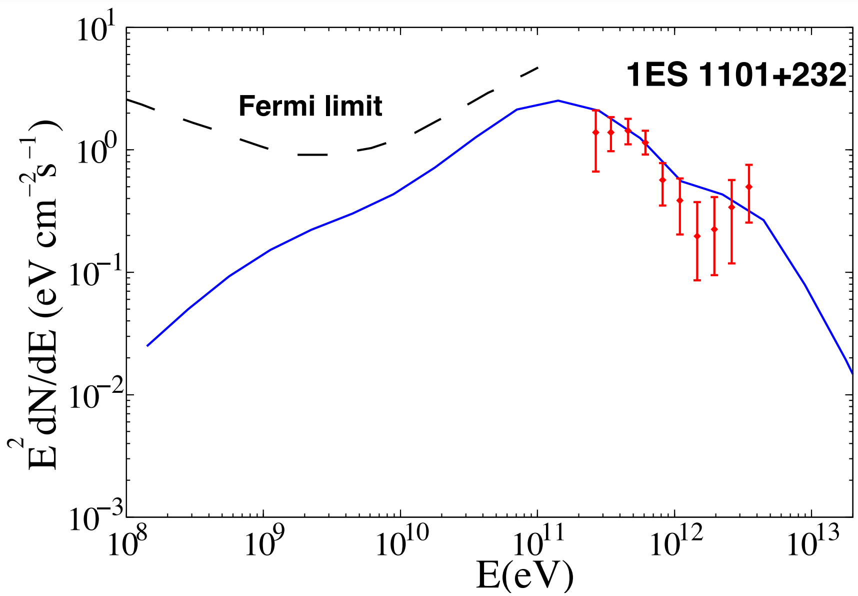
gamma rays (HESS)

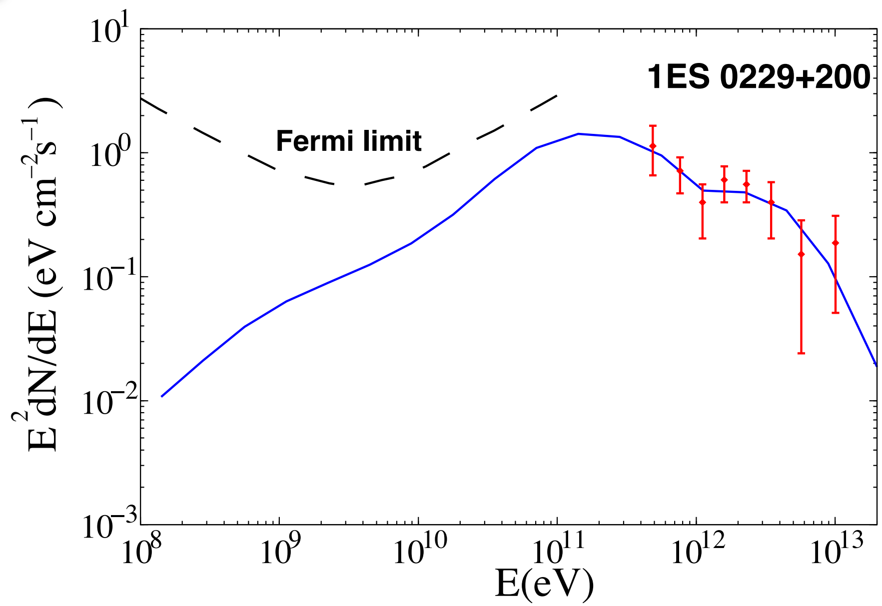
The shape of the spectrum is fixed by the EBL, the overall height is proportional to the product of UHECR luminosity and the level of EBL.

The effect of different E_{max} is to change the relative contribution of the different reactions to the flux of secondaries. If E_{max} is large (>10 EeV) interaction on CMB dominates, otherwise photo-pion production on EBL plays a role (provided that E_{max}>10^8 GeV).



Essey, Kalashev, Kusenko, Beacom (2011)





Conclusions

Gamma ray observations are of paramount importance in CR physics. Only through a multiple messengers analysis we can really validate theoretical models.

Galactic CR

Acceleration

- ✓ γ-rays from isolated SNR provide important test of the NLDSA paradigm (best example so far: Tycho)
- ✓ γ-rays from molecular clouds nearby SNR test the CR flux escaping the accelerator

Propagation

- ✓ Diffuse galactic γ-ray background and γ-rays emission from GMC gives information about the galactic spectrum of CR (in particular at low energy unaffected by solar modulation)

ExtraGalactic CR

- ✓ γ-rays extragalactic diffuse flux could help in solving the alleged discrepancy in the Auger and Telescope Array observations.
- ✓ γ-rays from isolated AGN can be related to the UHECR produced in the AGN, giving a direct link with an acceleration site.