Gamma ray astrophysics: the relation with cosmic rays and neutrino astrophysics

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The Future Research of Cosmic Gamma Rays
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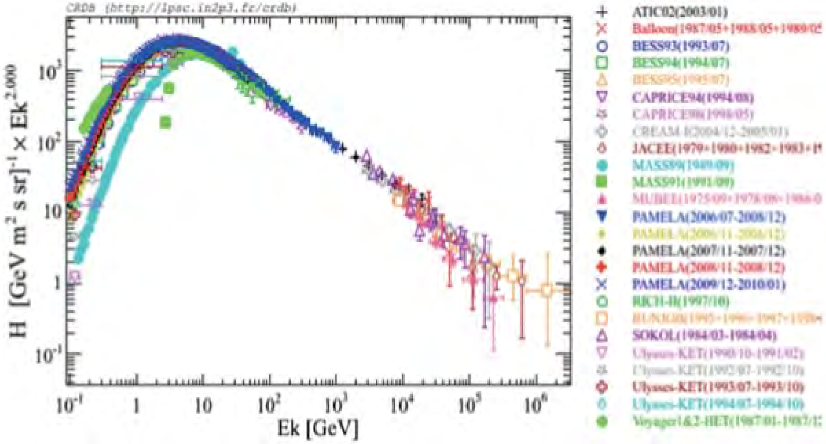
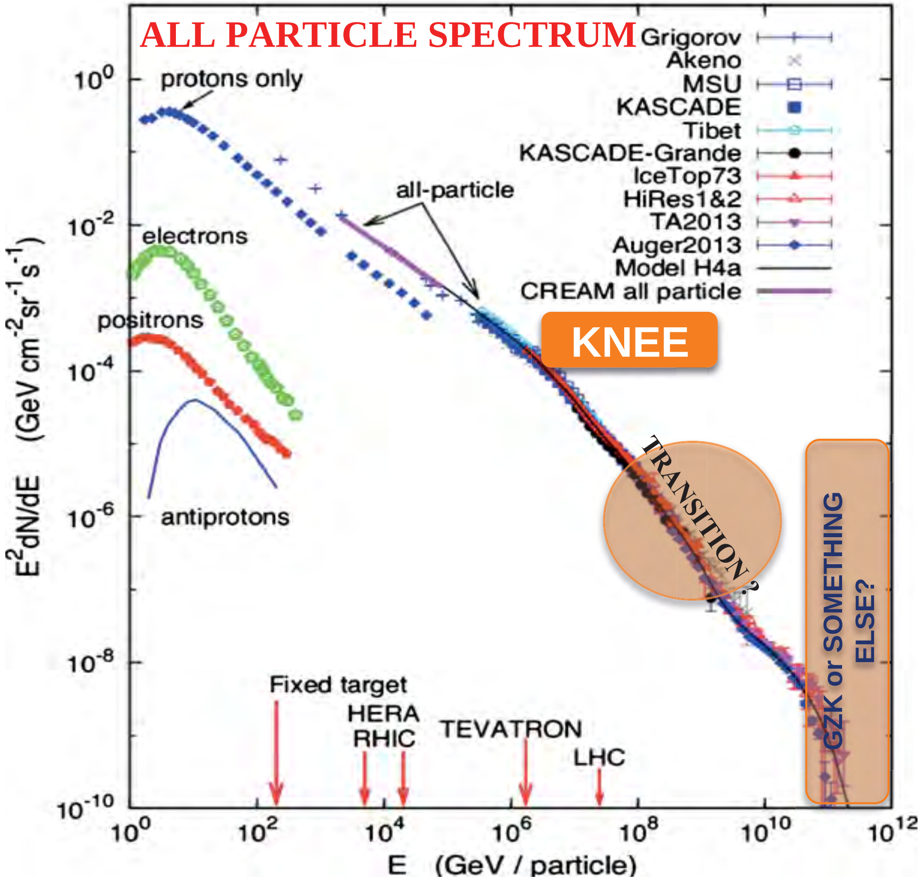
Cosmic Rays Spectra

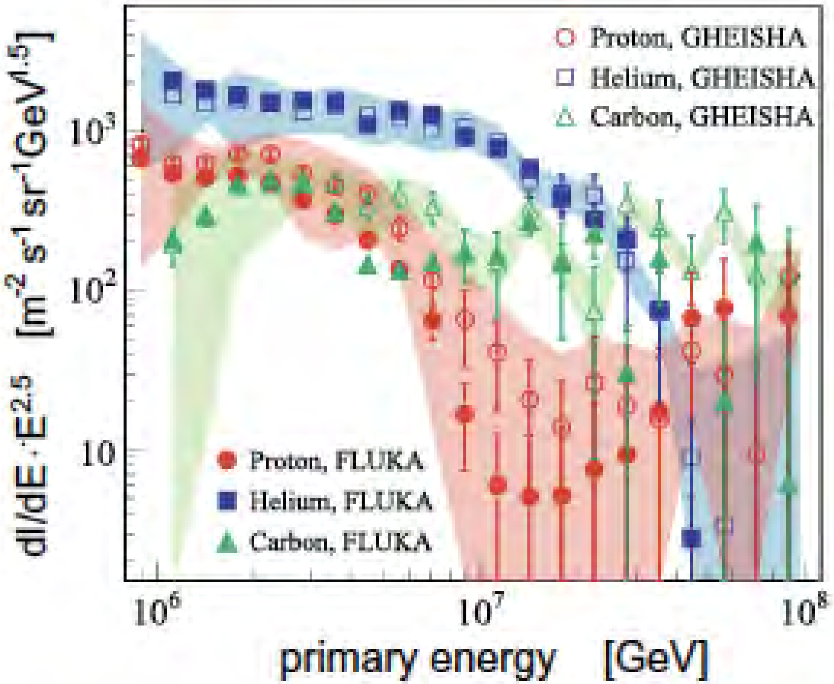
- ✓ The all particle spectrum has a (broken) power law behavior with few structures: knee, ankle, strong suppression at UHE.
- ✓ Changes in chemical composition and origin (Galactic/Extra-Galactic)

PROTON SPECTRUM



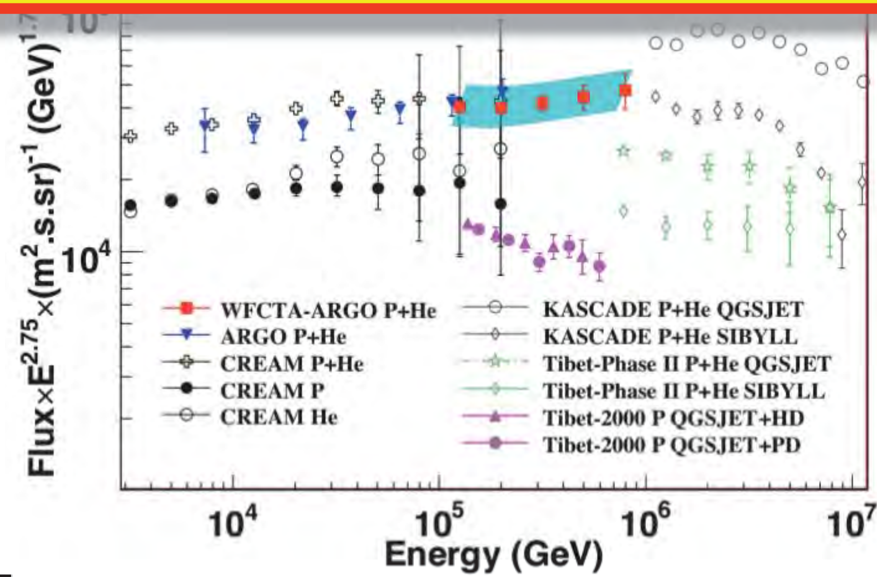


P+HE SPECTRUM (Kascade)

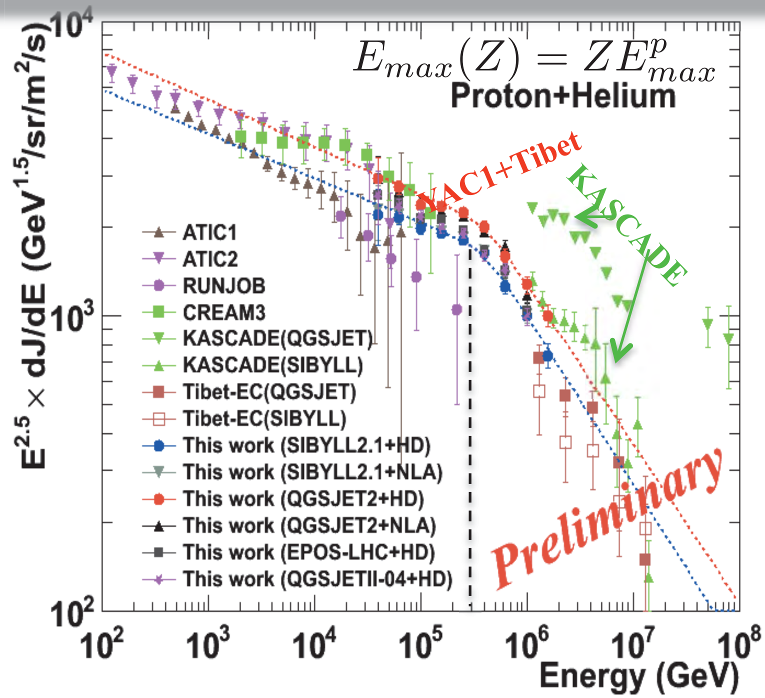


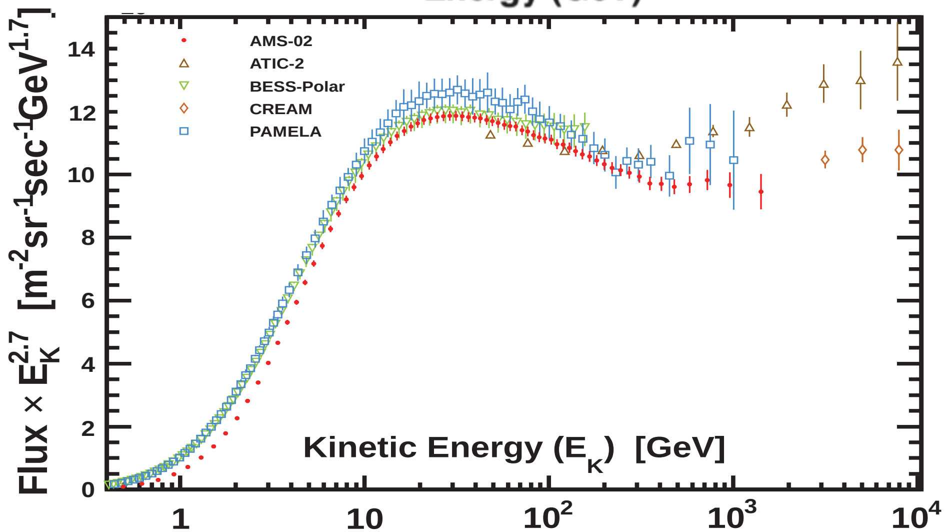
Some questions on CR

✓ Injection power law and relative abundances p,He



✓ Uncertainty in the knee position of p and He



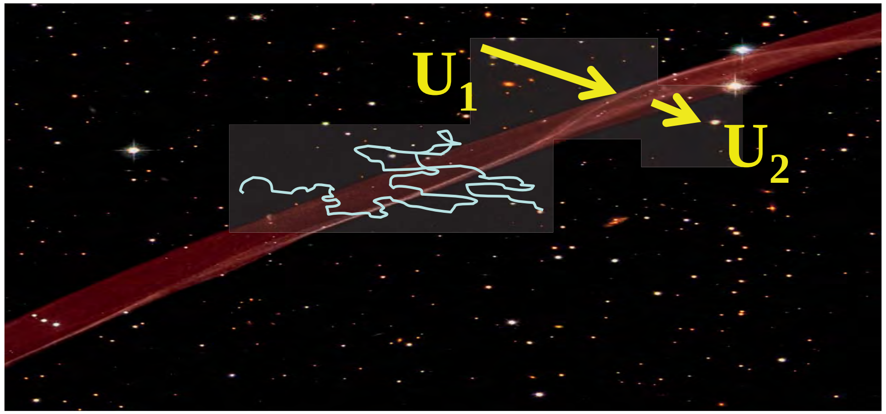


✓ Presence of spectral brakes

✓ 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



Maximum Energy

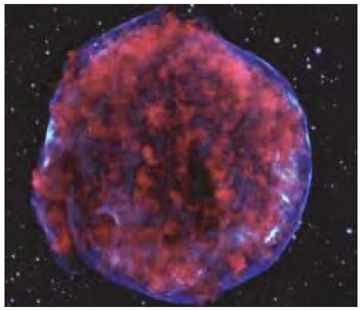
$$\tau_{diff} = \frac{D(E)}{V_{sh}^2} \leq \mathrm{Min}(\tau_{SNR}, \tau_{loss}, \tau_{esc})$$

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

X-rays observations

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

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



Comparison with the observed thickness leads to a B-field estimate

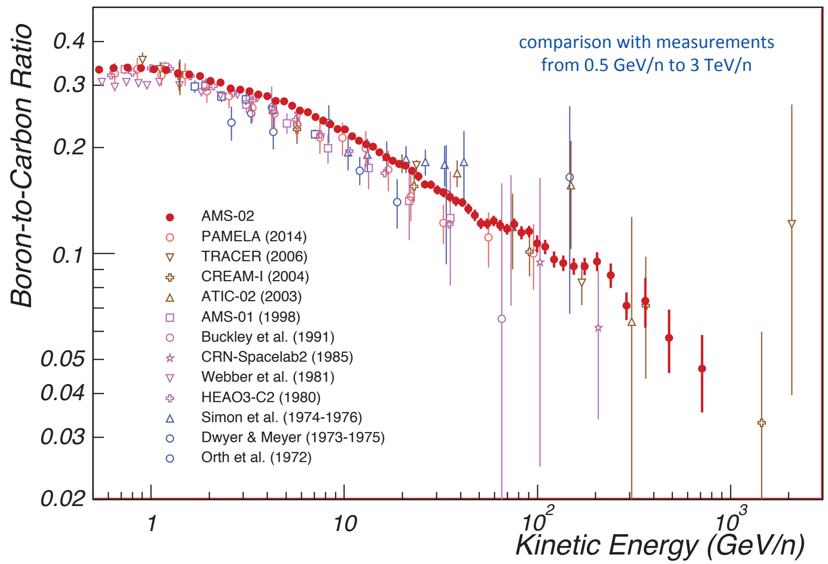
$$B \simeq 100 \mu G$$

- ✓ 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. Needs additional turbulence to achieve $10^5 \sim 10^6$ GeV.
- ✓ 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

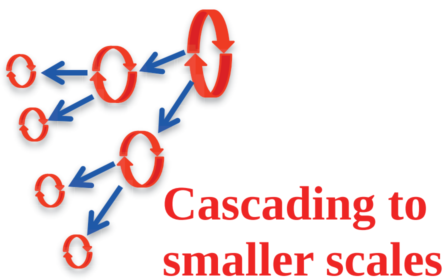
CR Propagation and self generated turbulence

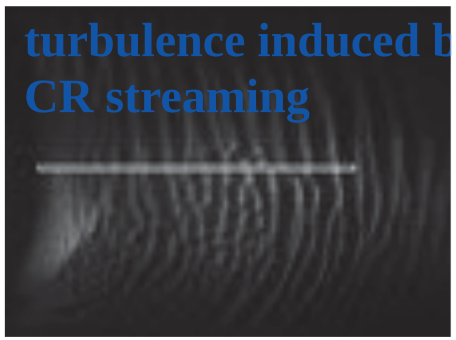
The decrease of B/C with energy/nucleon is the best sign of a rigidity dependent grammage traversed by CR on their way out of the galaxy. It confirms the picture of a diffusive propagation of CR

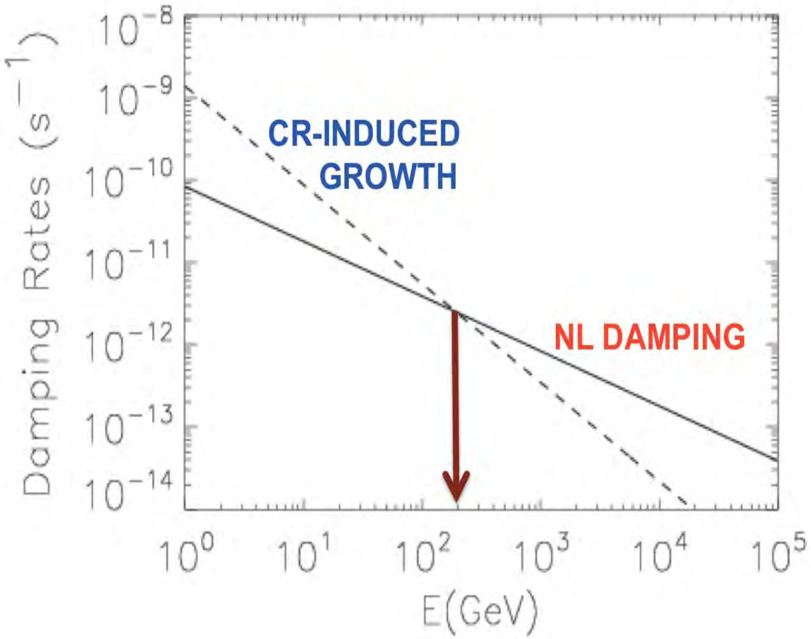
$$\frac{\Phi_B(E)}{\Phi_C(E)} \propto X(E) \propto \frac{1}{D(E)} \propto E^{-\delta}$$



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.

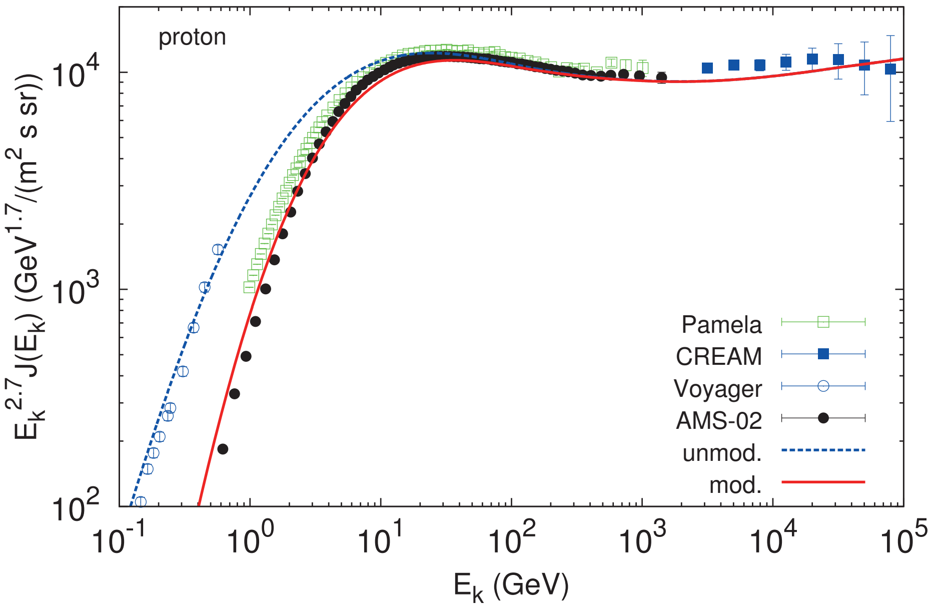


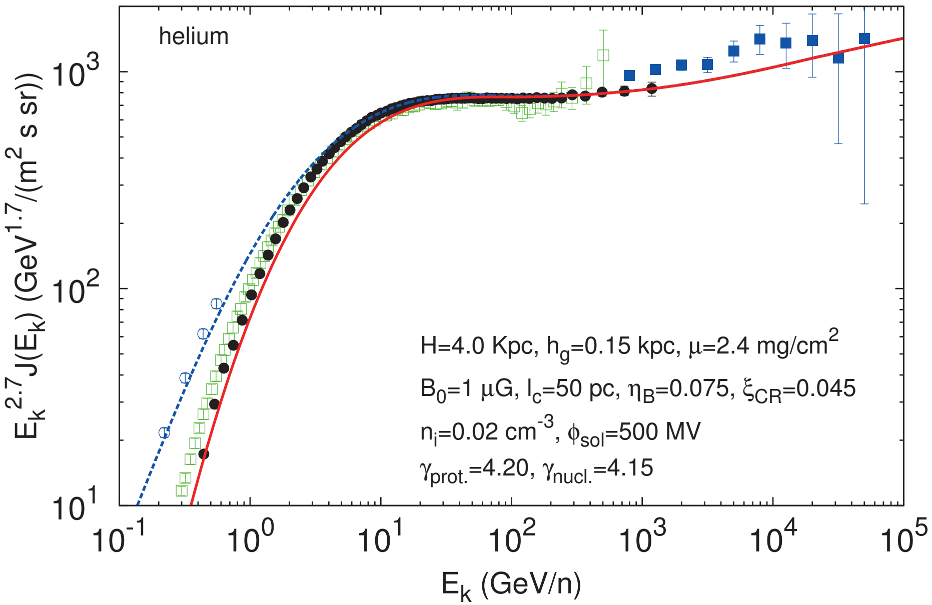


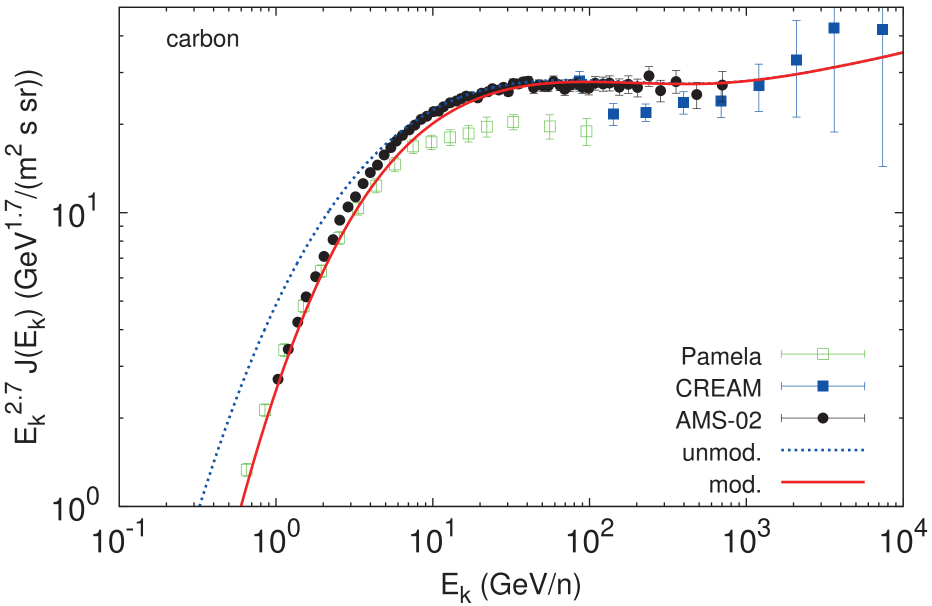


AMS-02 and Voyager

RA & Blasi (2013); RA, Blasi, Serpico 2015







- ✓ Proton and Helium fluxes observed by AMS-02 and Voyager are reproduced quite well.
- ✓ Voyager observations independent of solar modulation. True ISM flux of CR.
- ✓ Carbon flux observed by AMS-02 reproduced quite well.

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

- 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.

γ ray emission from SNR

Hadronic models

$$pp \rightarrow \pi^0 \rightarrow \gamma\gamma$$

γ rays emitted with the same spectrum of CR:

$$E^{-\gamma}$$

smoking gun of this mechanism is the pion bump: not yet observed in SNR

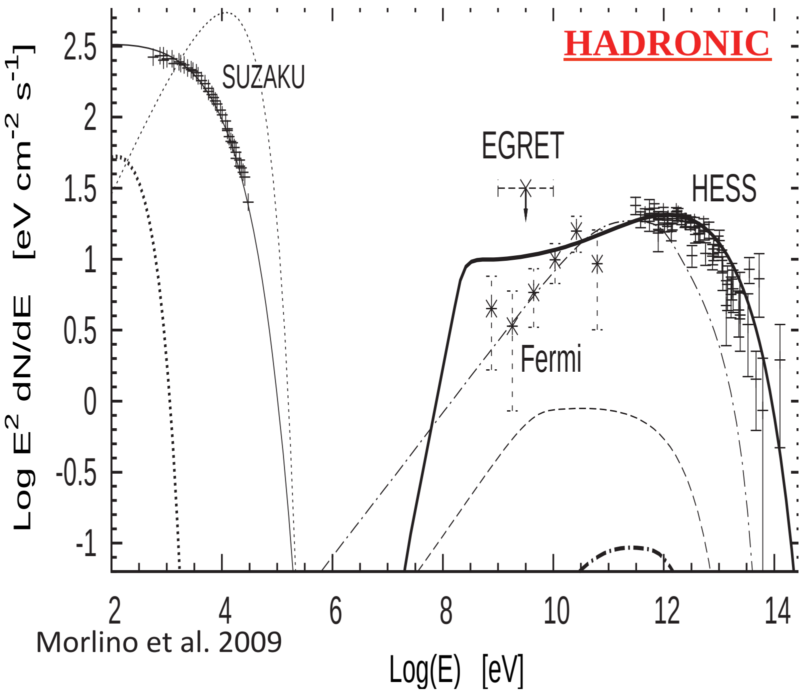
Leptonic models

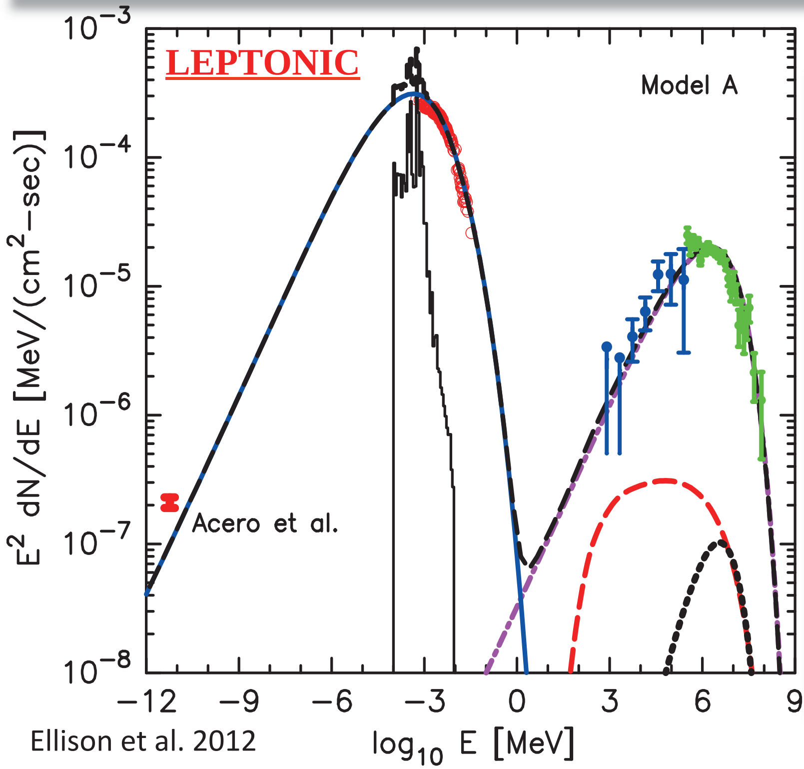
Gamma rays are produced by the Inverse Compton scattering of relativistic electrons on photons backgrounds.
The spectrum of gamma rays emitted has a flatter behavior respect to CR

$$E^{-(\gamma+1)/2}$$

The case of RXJ1713

- observed in keV, GeV and TeV range
  Bamba et al. (2009); Aharonian et al. (2004-2007); Abdo et al. (2011)
- X-ray rims observed with B~160 μG are compatible with CR acceleration
- hadronic origin of GeV-TeV emissions can be possible

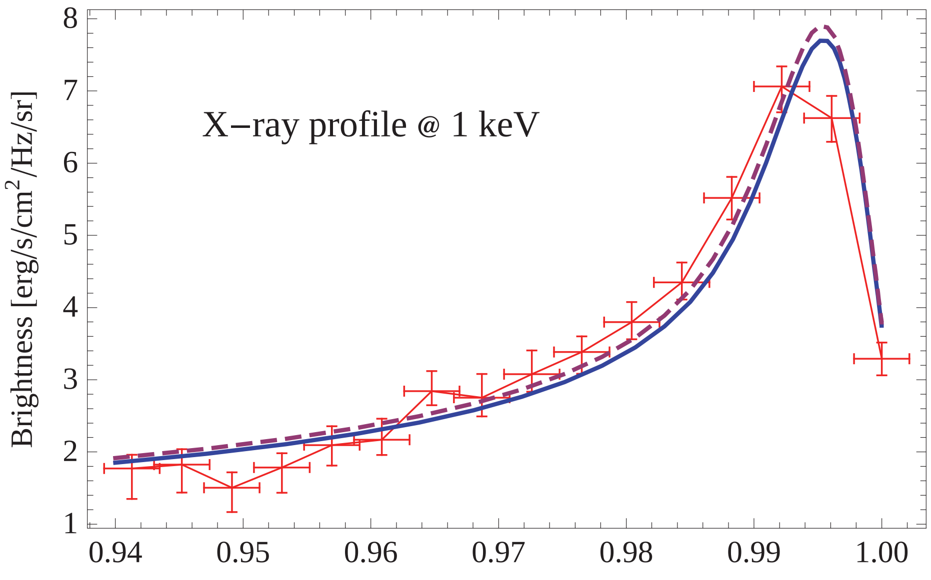




- No oxygen lines observed, very small densities, less efficient pp interactions.
- leptonic origin of GeV-TeV emissions requires high IR light (~20 times than observed) and too low B (if compared to X-ray emission).
- complex environment, future high resolution gamma ray observations will distinguish different emitting regions.

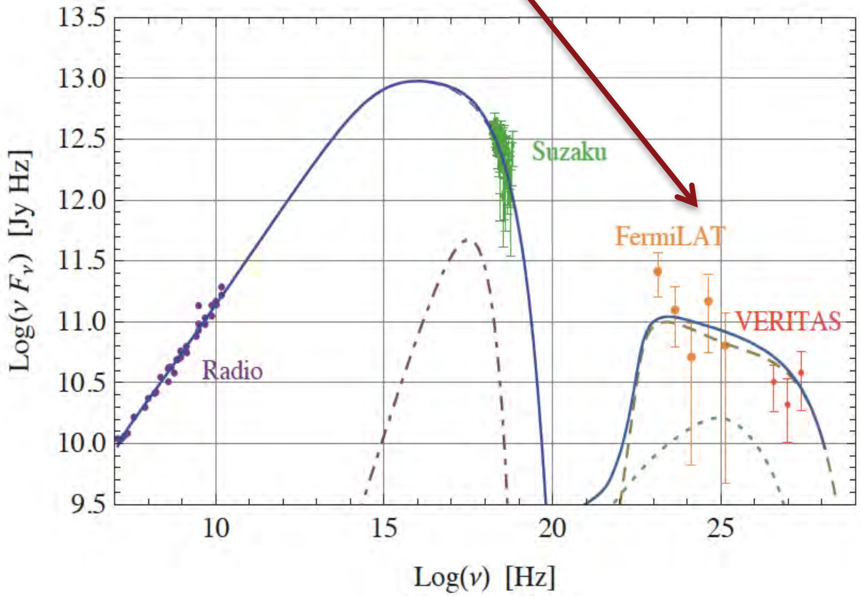
The case of Tycho

- ✓ 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



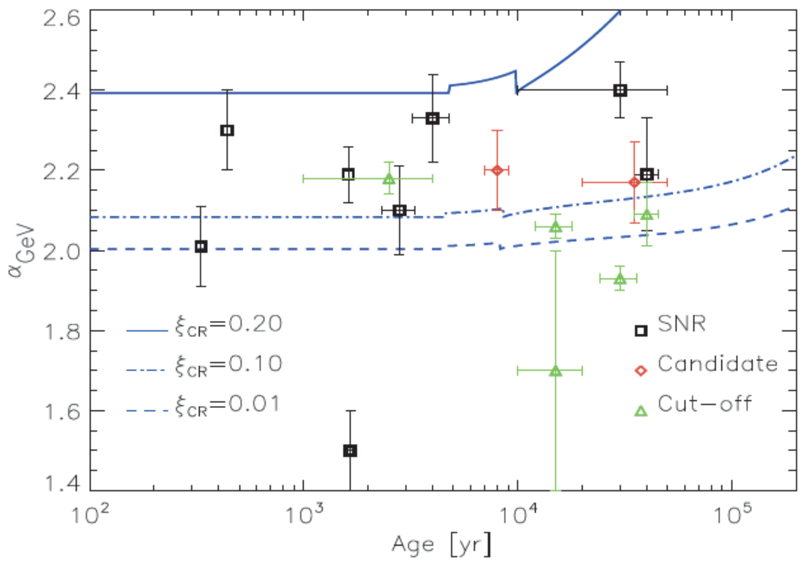
Morlino & Caprioli 2011

- ✓ 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 DSA. 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

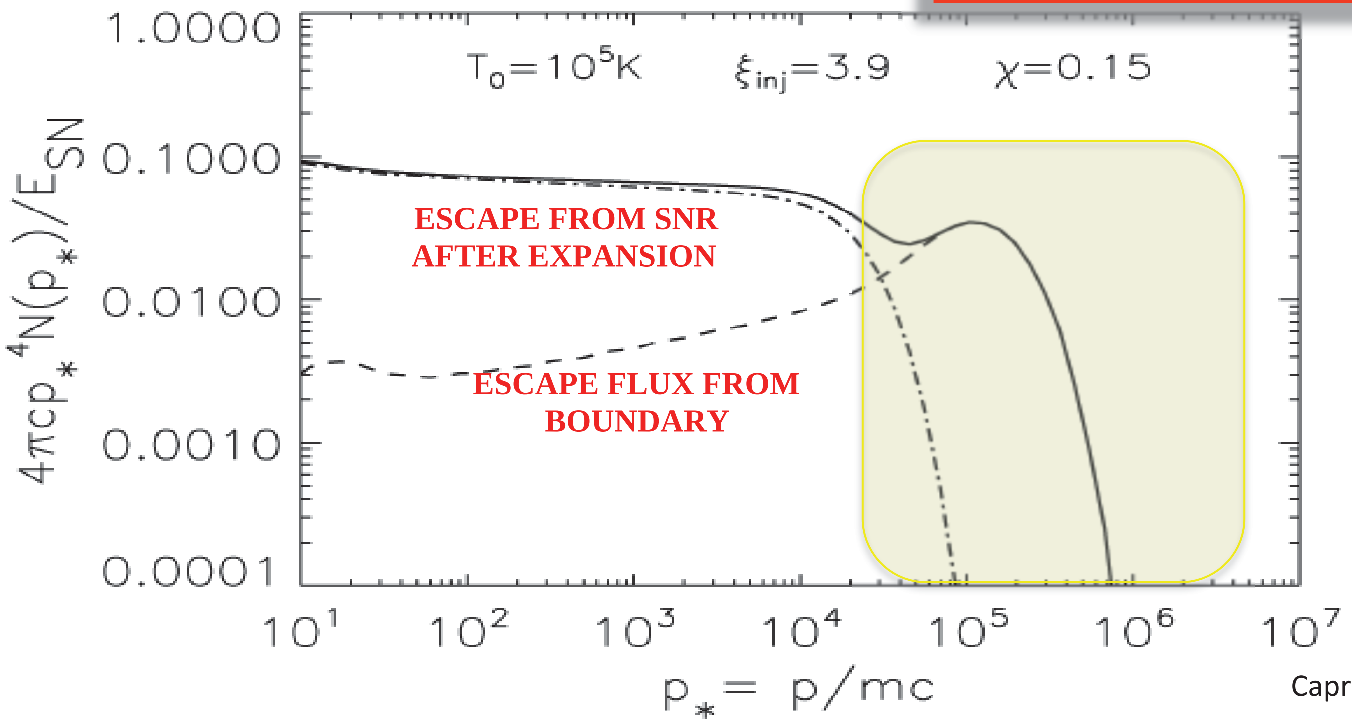


Caprioli et al. 2011

- ✓ 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

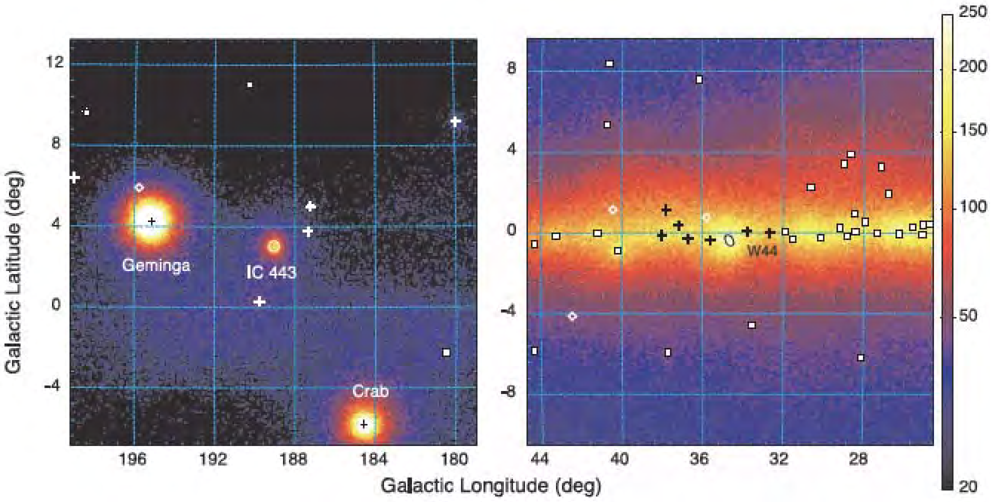
- ✓ particles escaped during the Sedov-Taylor phase (emission peaked on p_{max})
- ✓ particles released in the ISM after expansion

γ ray emission from molecular clouds

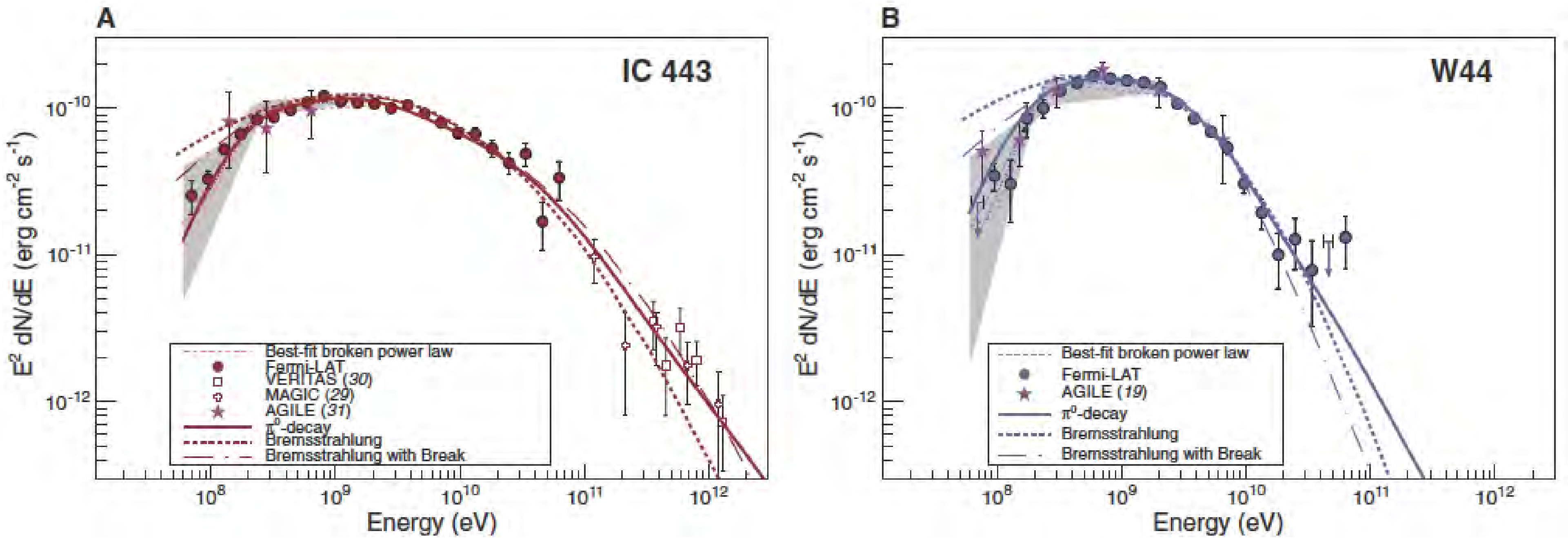
- ✓ Firm observation of the pion bump

$$pp \rightarrow \pi^0 \rightarrow \gamma\gamma$$

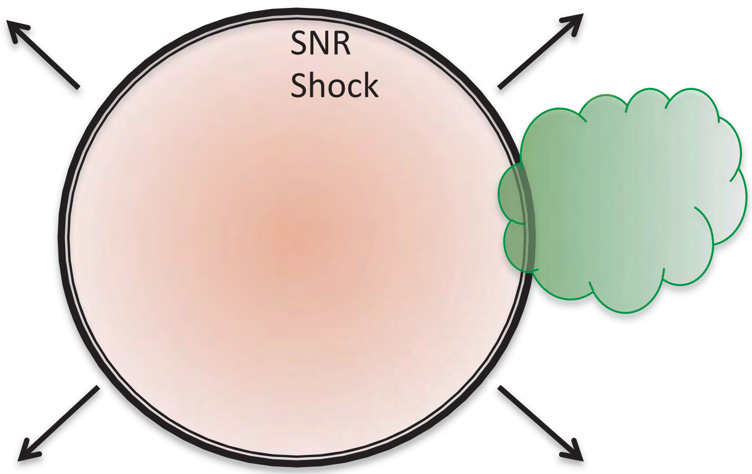
- ✓ SN close to molecular clouds are very interesting laboratories to investigate CR propagation around sources and escape from sources.



Ackermann et al. 2013



Shock inside the cloud

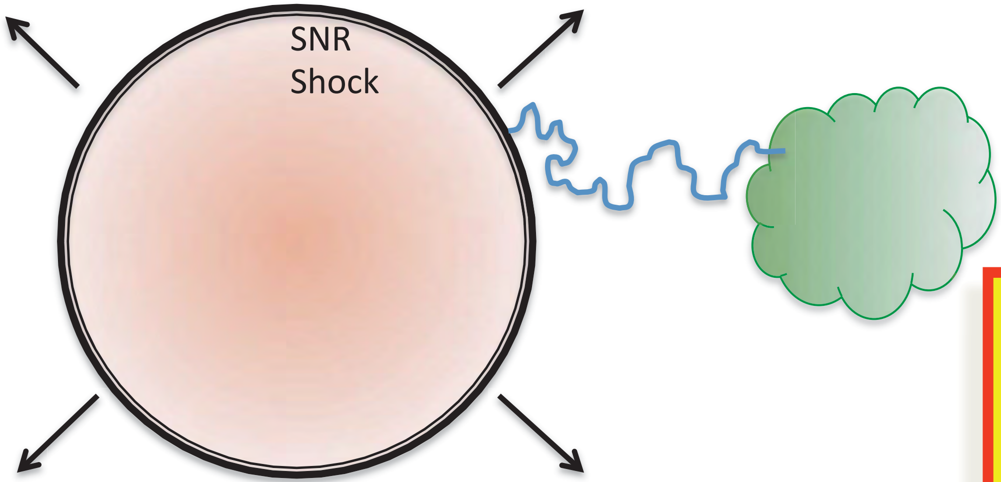


- the shock becomes collisional on scales

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

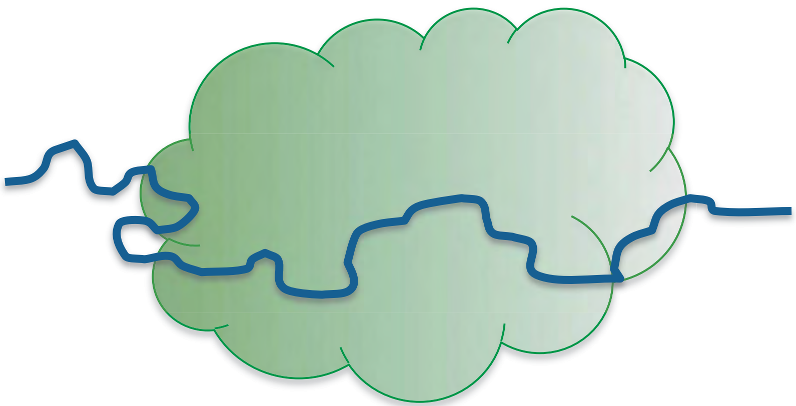
- It slows down since it feels the matter in the cloud, particle already accelerated escape streaming away and interacting with matter in the molecular cloud.

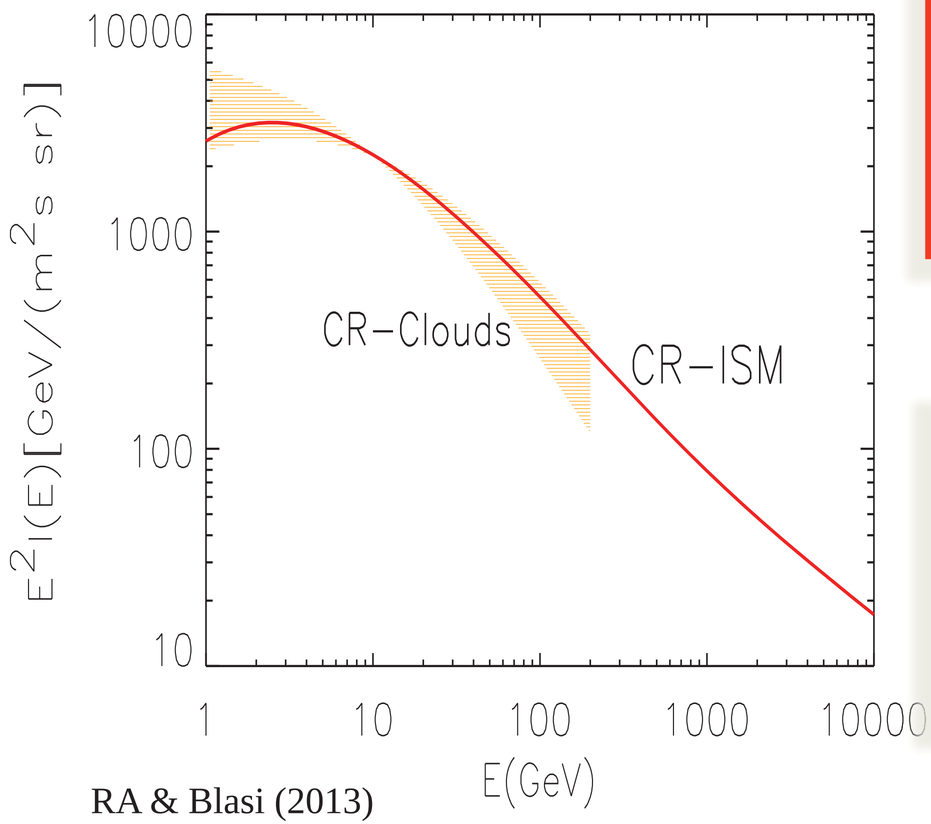
Shock outside the cloud



- γ-rays produced by CR reproduce the CR spectrum injected in ISM.
- γ-rays emission in this case could give direct information on the escaped flux of CR.

Gamma rays from isolated MC





RA & Blasi (2013)

This case is of particular importance in the study of the diffusive propagation of CR, offering the unique possibility of determining the CR spectrum unaffected by local effects such as the solar modulation. An interesting instance of these systems is represented by the γ-ray emission, already detected by by COS-B, EGRET and more recently by Fermi, from the Gould Belt clouds, the nearest Giant Molecular Cloud (GMC).

Observations of gamma rays from isolated Molecular Clouds can give important insights on the CR propagation models.
Possible confirmation of changes in the slope, non linear effects in propagation.

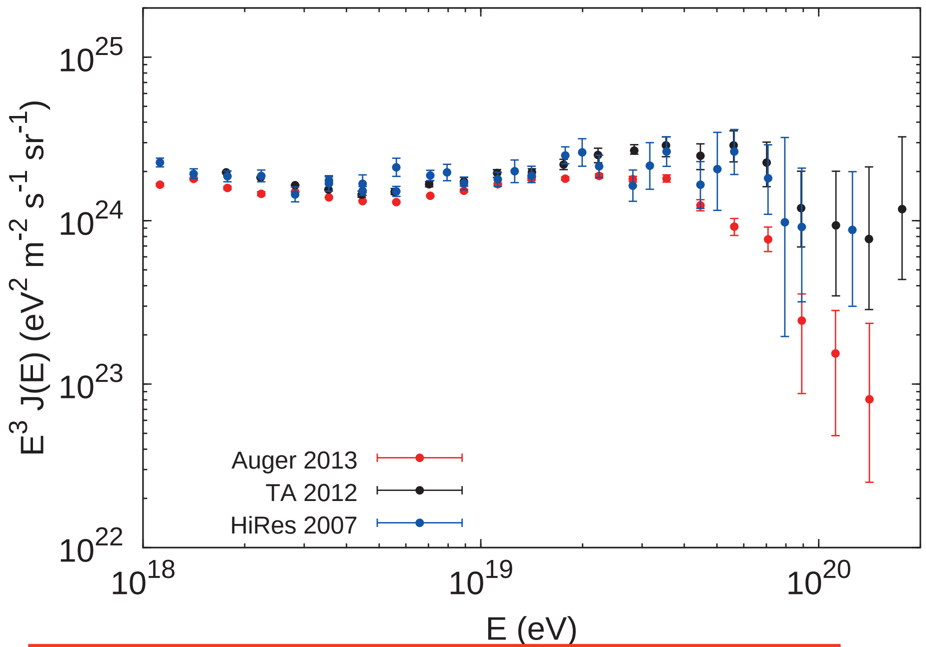
γ rays from molecular clouds – quick summary

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

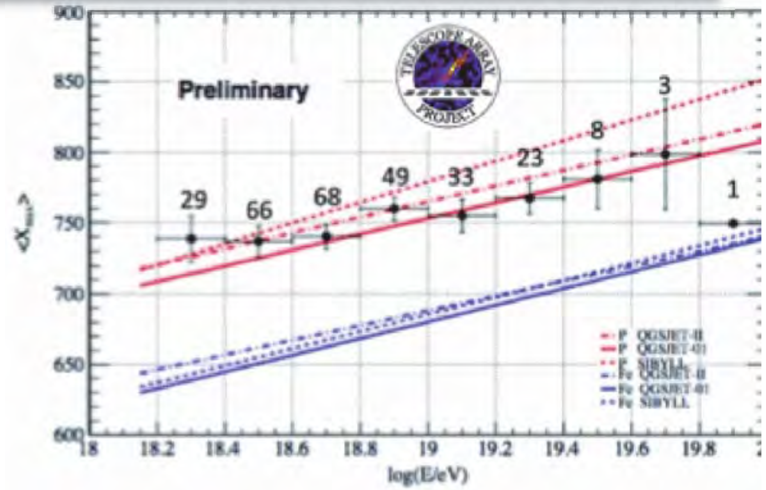
- ✓ The two contributions to the injected spectrum (i.e. from escaped particles and particles released after the end of expansion) can be disentangled looking at the gamma ray emission from clouds.

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

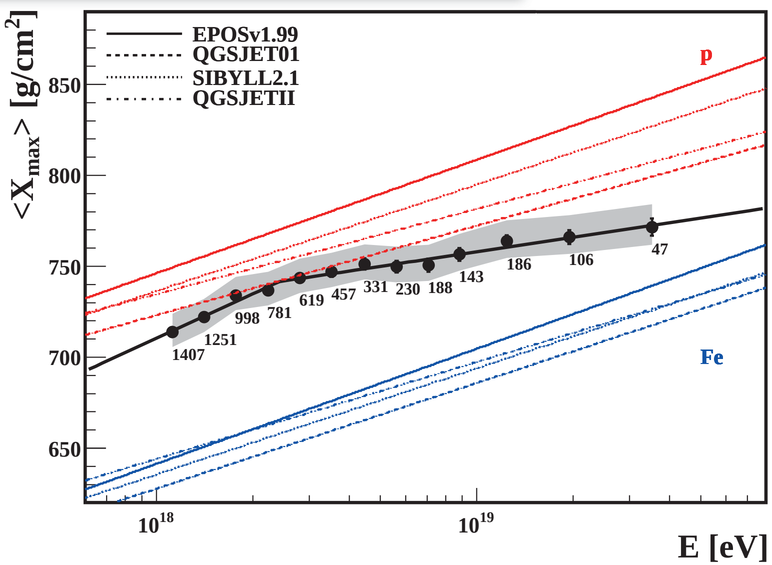
CR at Ultra High Energies

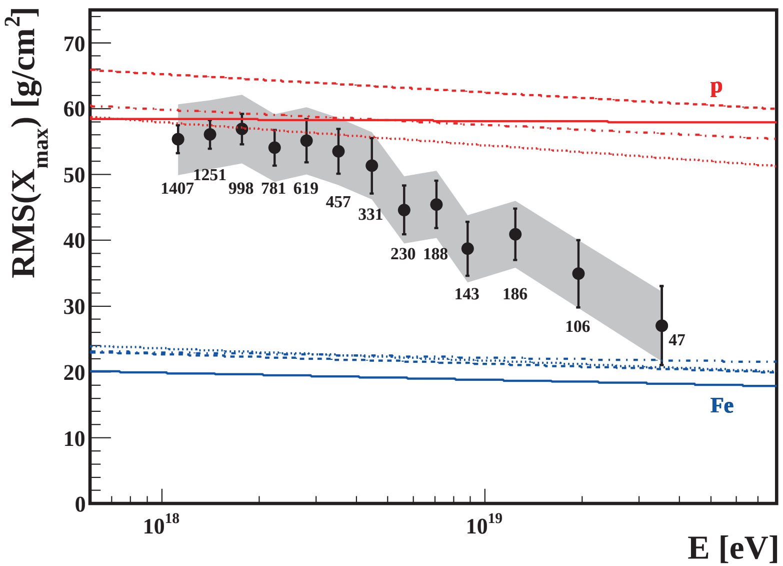


✓ HiRes-TA points toward a pure proton composition at all energies.



✓ Auger observes an increasing heavy composition at the highest energies

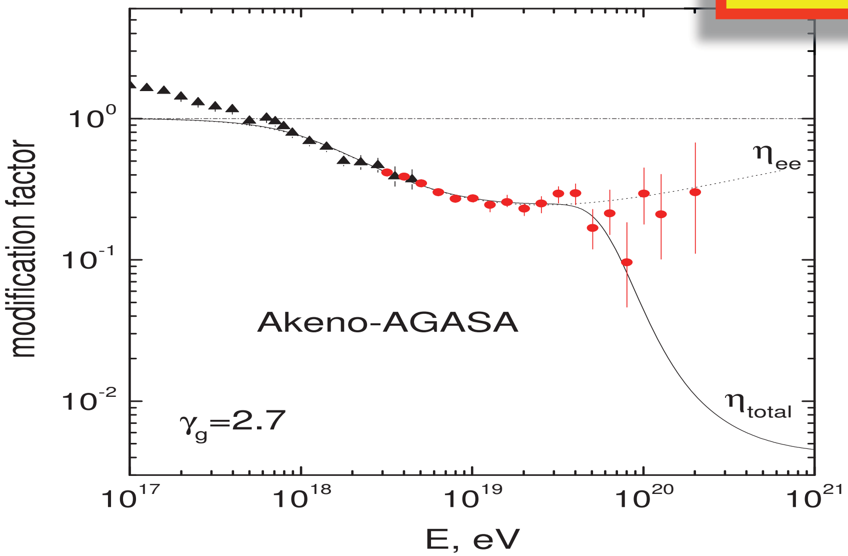


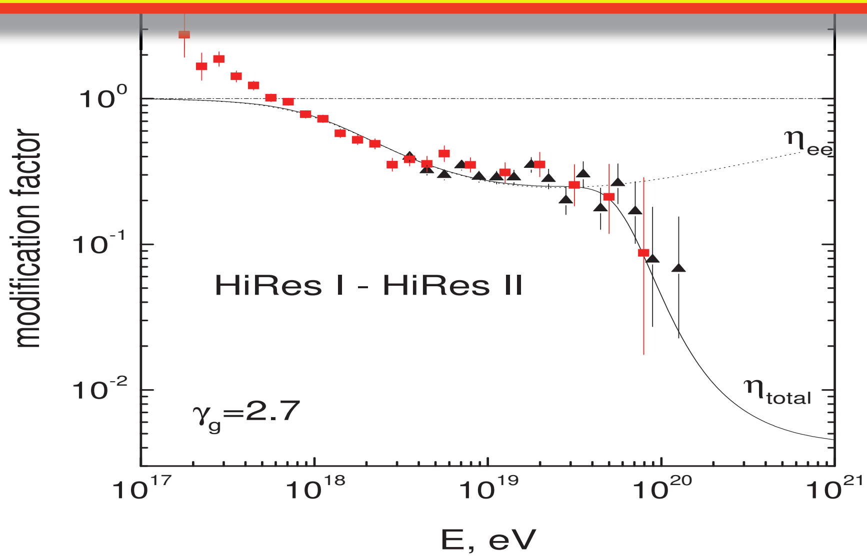


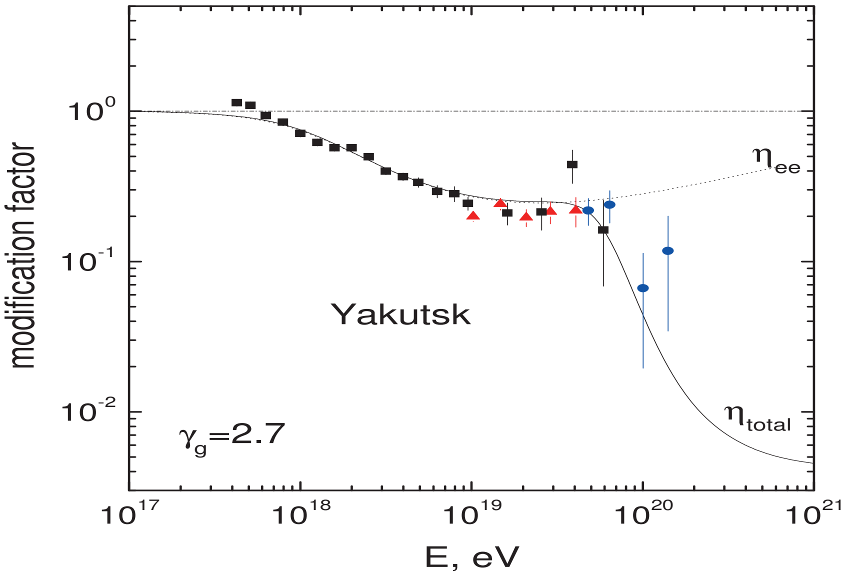
Dip Model

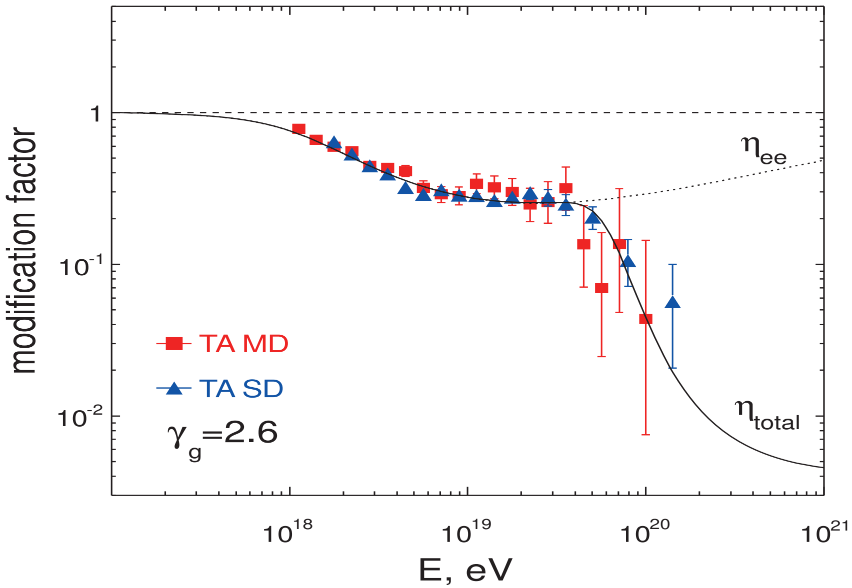
the protons footprint

In the energy range 10^{18} - $5x10^{19}$ eV the spectrum behavior is a signature of the pair production process of UHE protons on the CMB radiation field.



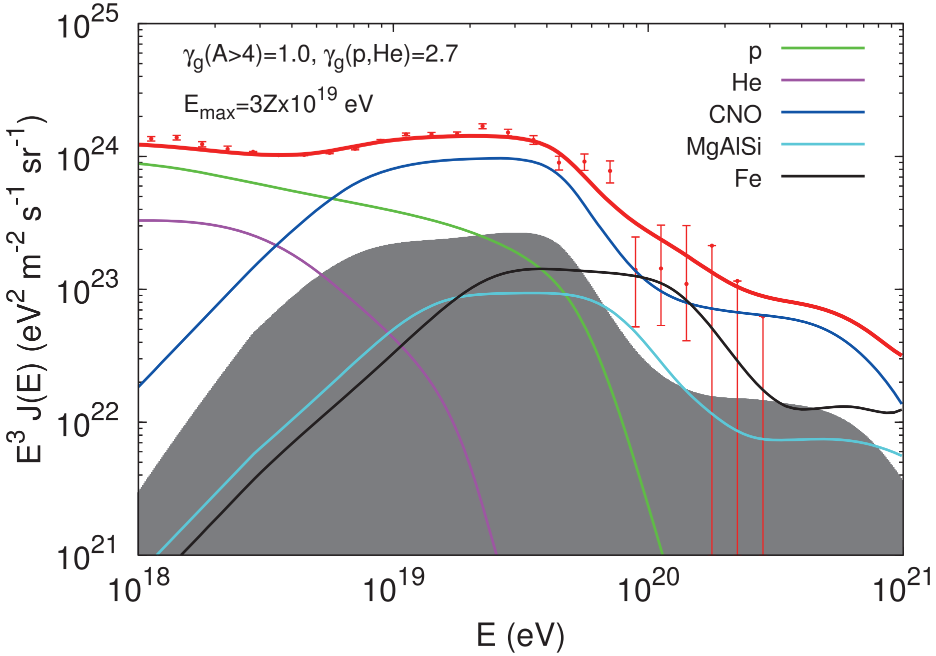






Berezinsky et al (2002) - RA et al. (2007-2012)

Mixed Composition



Two types of extra-galactic sources:

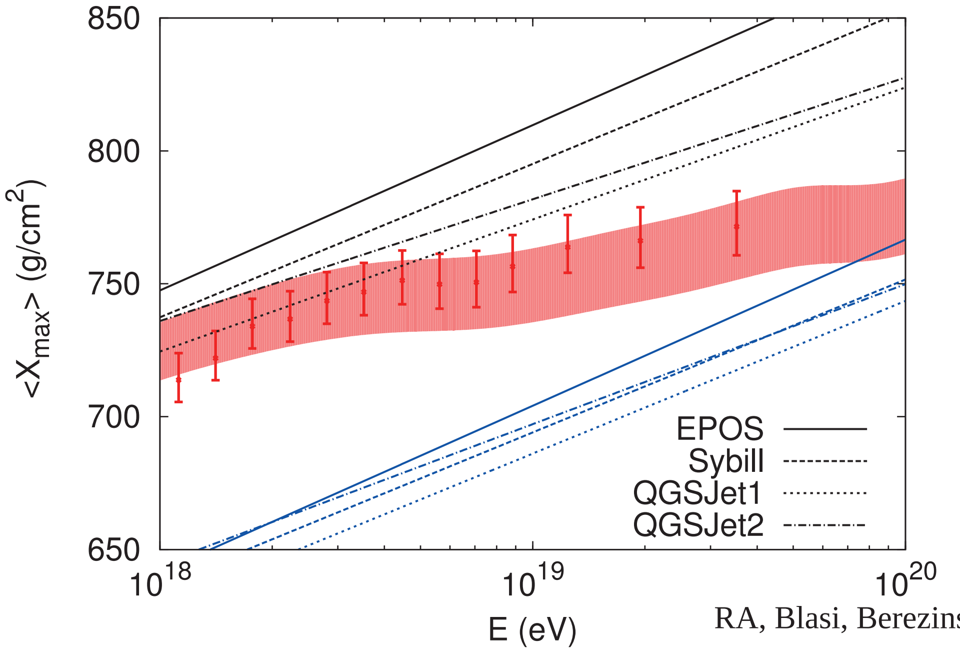
- ✓ light component steep injection (γ_g>2.5)

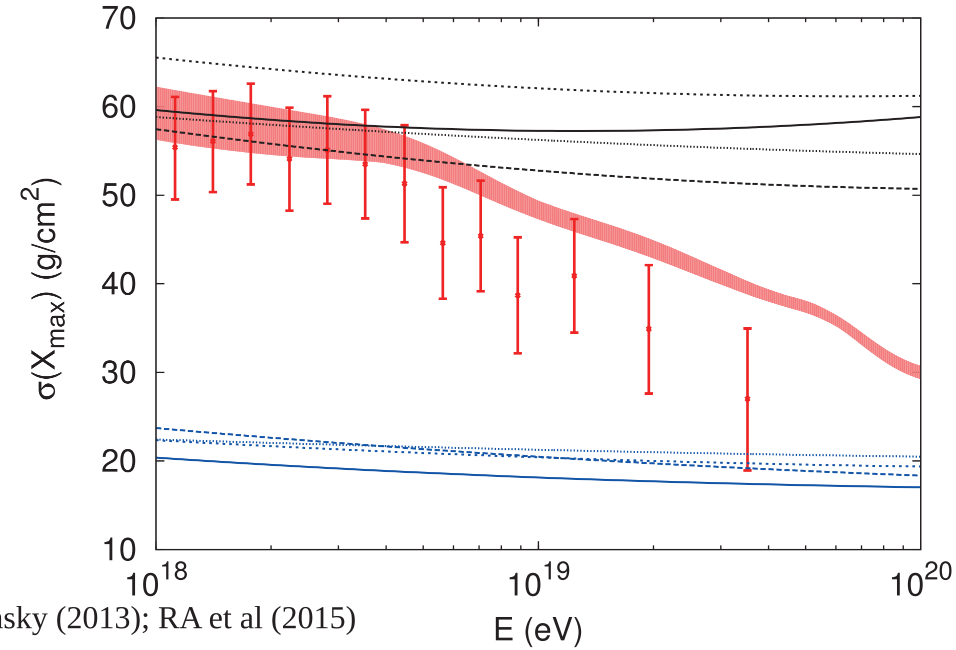
$$\mathcal{L}_0 = n_{UHE} L_{UHE} \simeq 10^{47} \frac{\text{erg}}{\text{Mpc}^3 \text{y}}$$

- ✓ 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



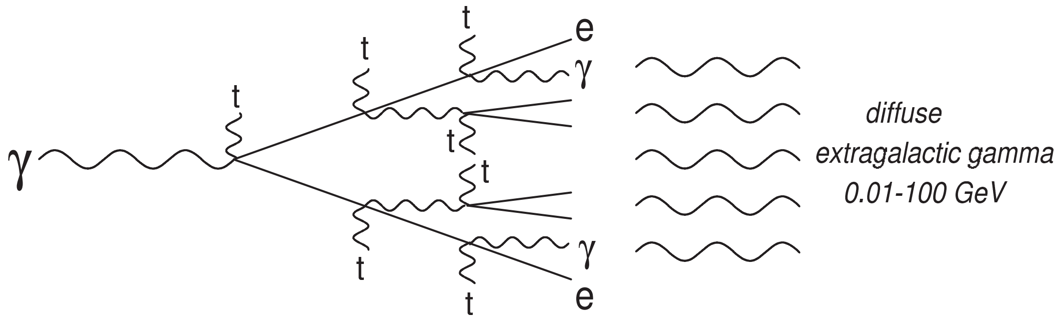


RA, Blasi, Berezinsky (2013); RA et al (2015)

Production of secondary γ ν

Cascade upper limit

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



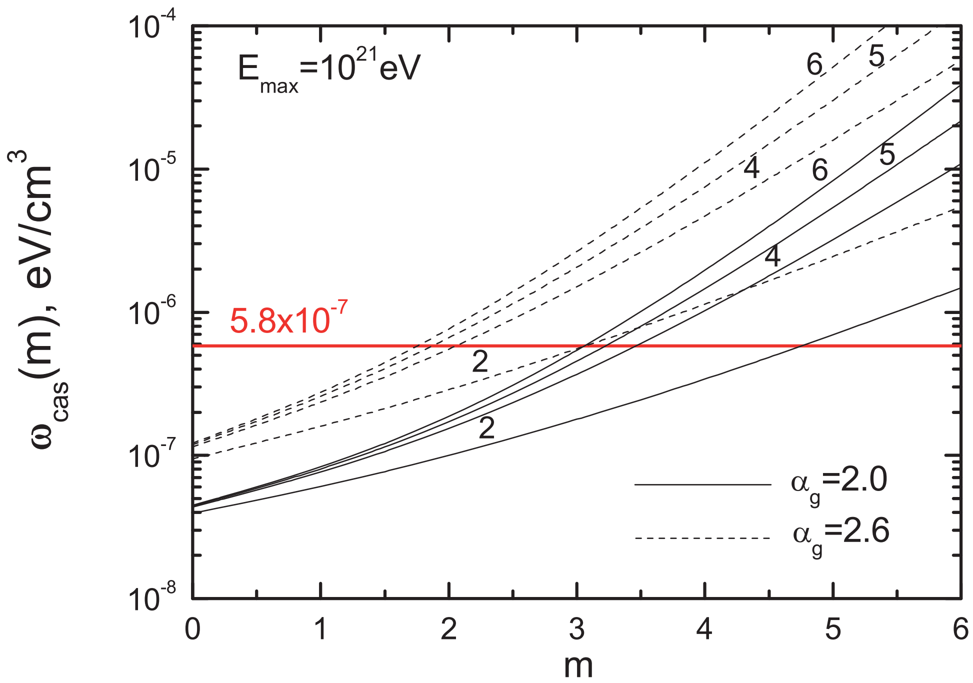
Fermi-LAT data

$\omega_{cas} = 5.8\text{x}10^{-7}$ eV/cm^3

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

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.

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

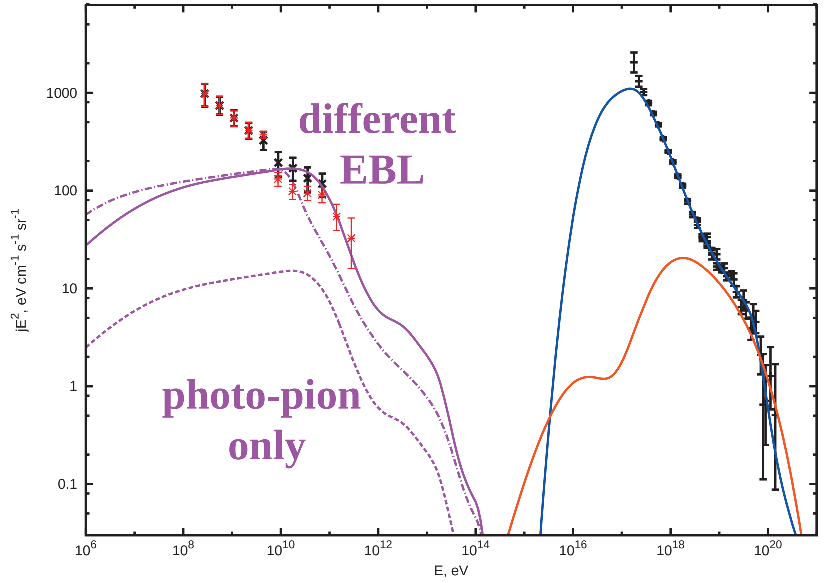
Dip model: γ - ν diffuse spectra

TeV photons produced by pair-production on CMB and EBL backgrounds. EBL evolution models are relevant (Fermi-LAT).

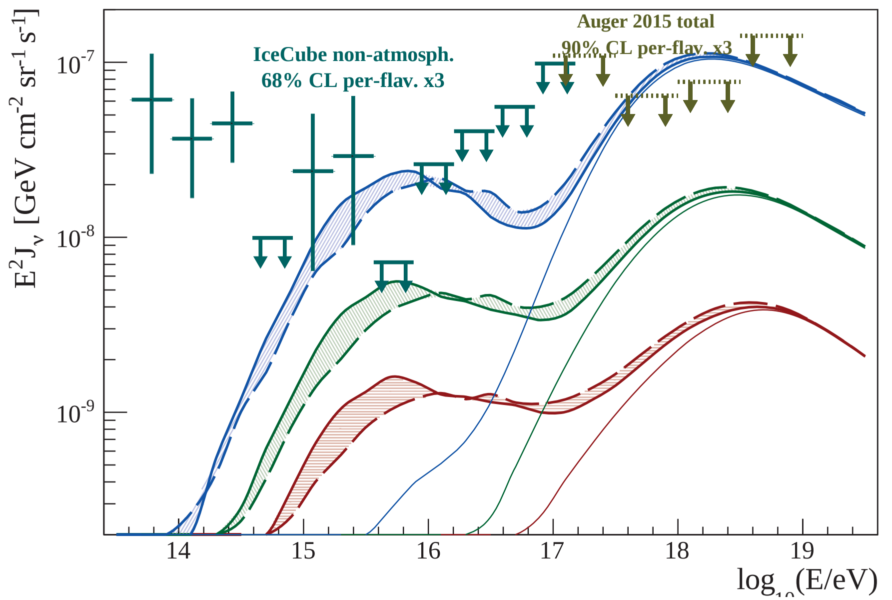
- ✓ Photo-pion production on EBL has a threshold of about 10^8 GeV, broadened by the energy distribution of EBL photons. UHE protons on the EBL can account for the production of PeV neutrinos.
- ✓ The result on the diffuse flux depends on the cosmological evolution of sources. The IceCube observations at PeV can be marginally reproduced in the case of strong cosmological evolution (AGN like)

The PeV neutrino flux and TeV gamma flux provide constraints on the sources of UHECR and their cosmological evolution.

Gelmini, Kalashev, Semikoz (2012); Giacinti et al. (2015)



RA, Boncioli, di Matteo, Grillo, Petrera, Salamida (2015)



Mixed composition: γ - ν diffuse spectra

✓ TeV gamma rays

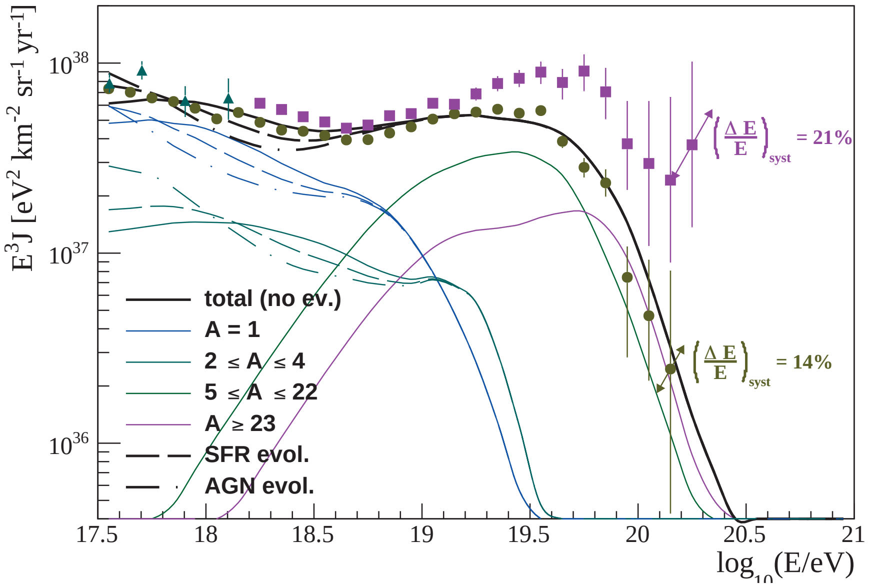
In the case of mixed composition no gamma ray signal is expected from UHECR.

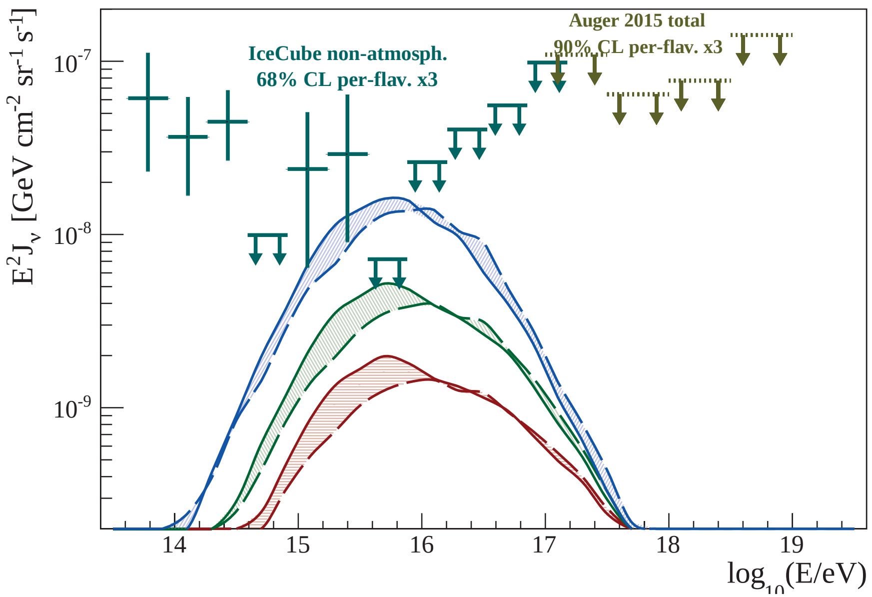
✓ EeV neutrinos

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

✓ PeV neutrinos

PeV neutrinos produced in the photo-pion production process of UHECR on the EBL radiation field The IceCube observations at PeV can be marginally reproduced in the case of strong cosmological evolution (AGN like).





RA, Boncioli, di Matteo, Grillo, Petrera, Salamida (2015)

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 (10^{-15} G).

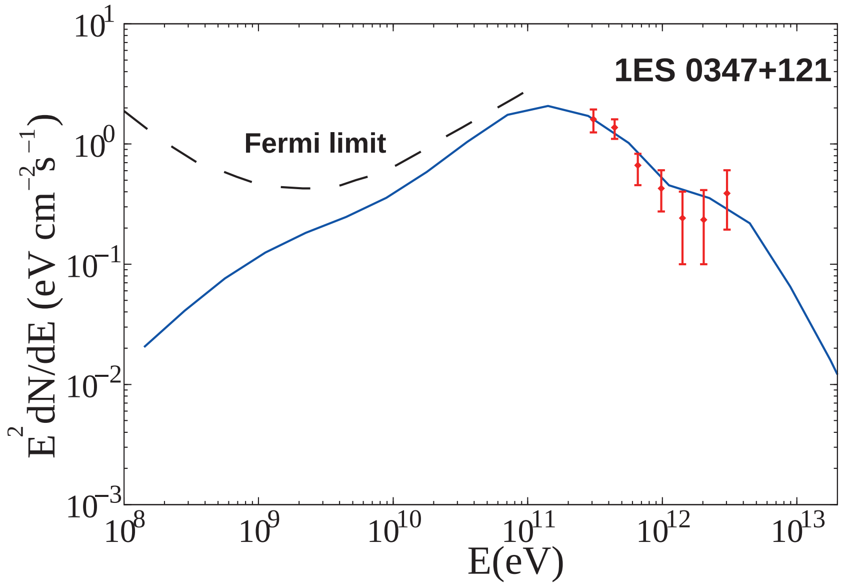
The spectrum of the final cascade is universal. The EM cascade behaves as a sort of calorimeter that redistribute the initial energy into gamma rays and neutrinos with a given spectrum.

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

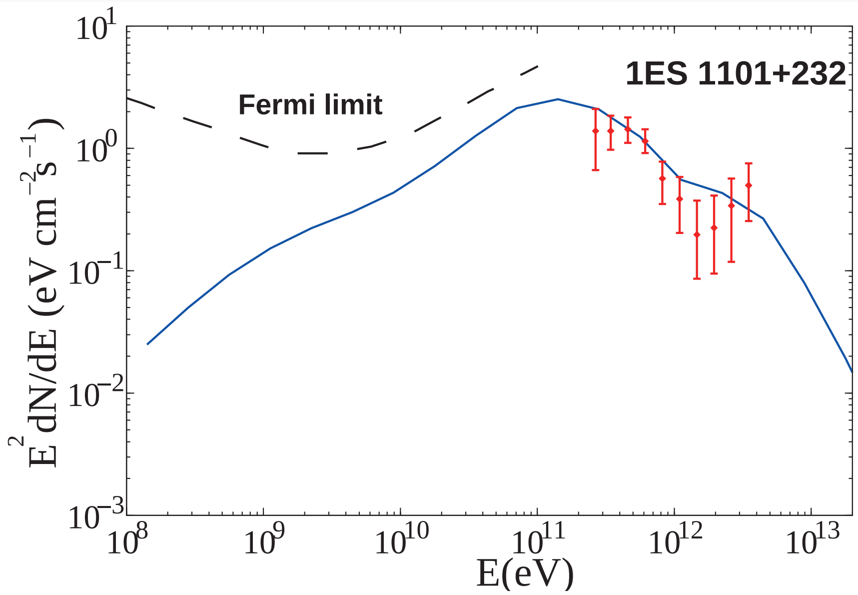
The shape of the spectrum is fixed by the EBL, the overall height is proportional to the product of UHECR luminosity and the level of EBL.

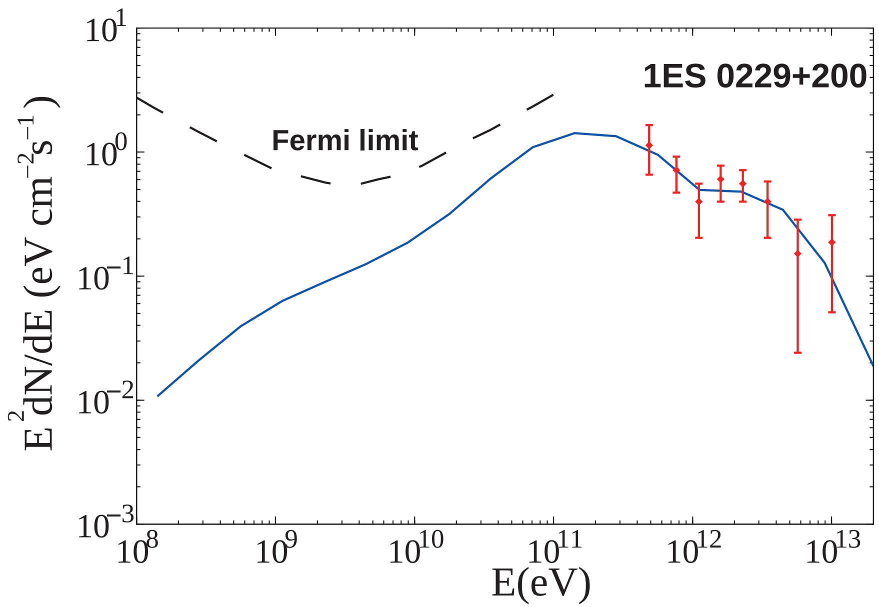
The effect of different E_{max} is to change the relative contribution of the different reactions to the flux of secondaries. If E_{max} is large (>10 EeV) interaction on CMB dominates, otherwise photo-pion production on EBL plays a role (provided that $E_{max} > 10^8$ GeV).

gamma rays (HESS)



Essey, Kalashev, Kusenko, Beacom (2011)





Conclusions

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

Galactic CR

Acceleration

- ✓ γ-rays from isolated SNR provide important test of the DSA 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 and ν 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 acceleration sites.