Cosmic Rays Physics: Sources and Fundamental Physics

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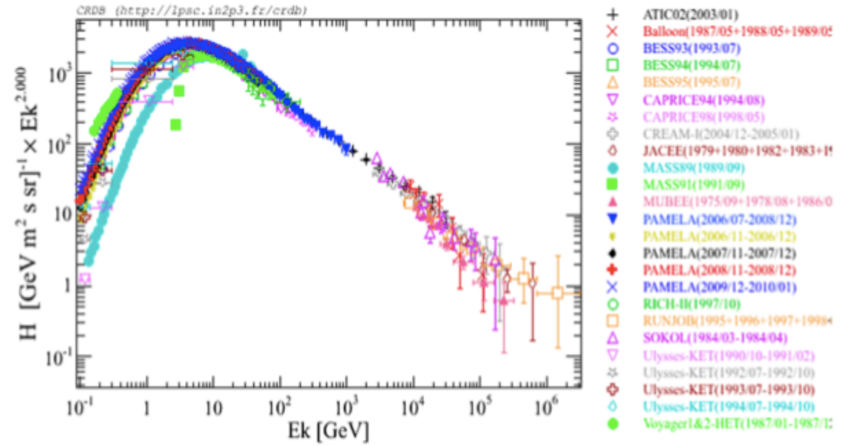
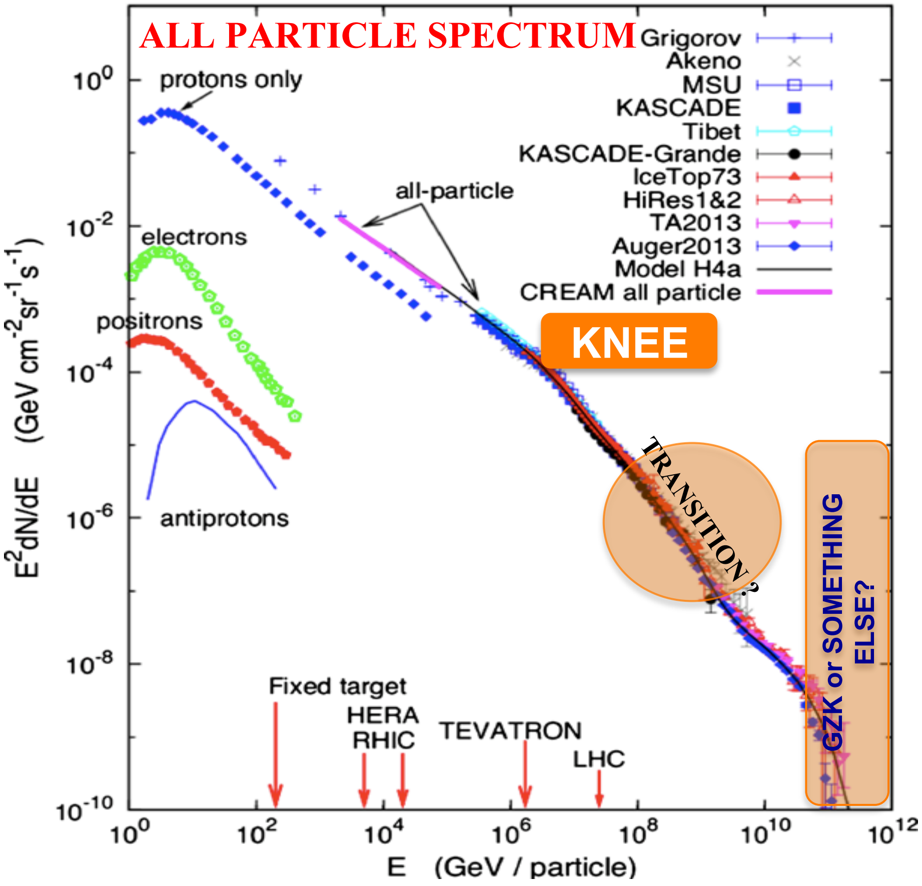
Cosmic Rays Spectra

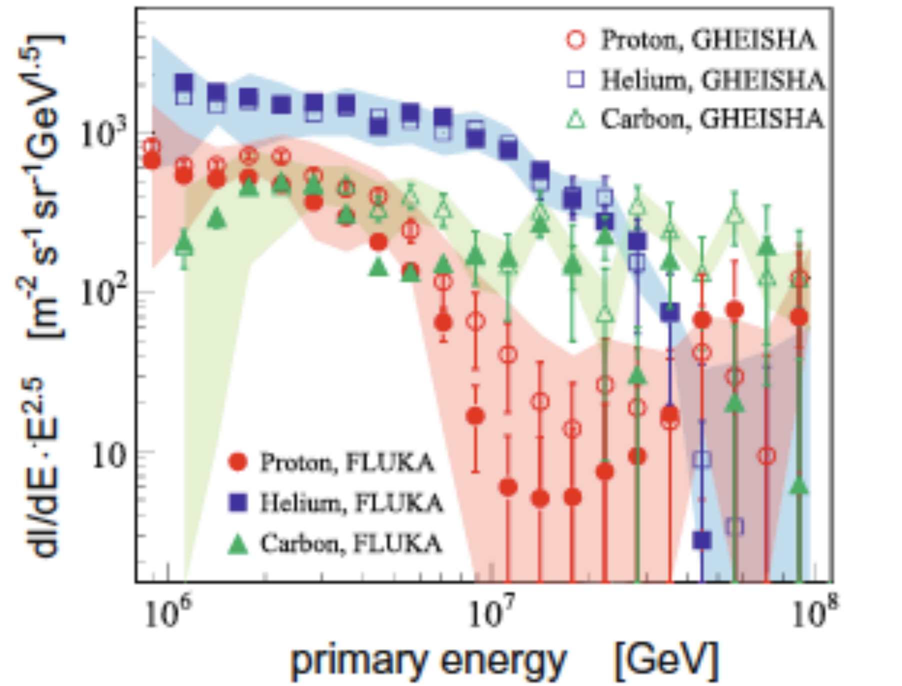
- ✓ The all particle spectrum has a (broken) power law behavior with few structures: knee, ankle, strong suppression at UHE.
- ✓ Changes in chemical composition and origin (Galactic/Extra-Galactic)

PROTON SPECTRUM



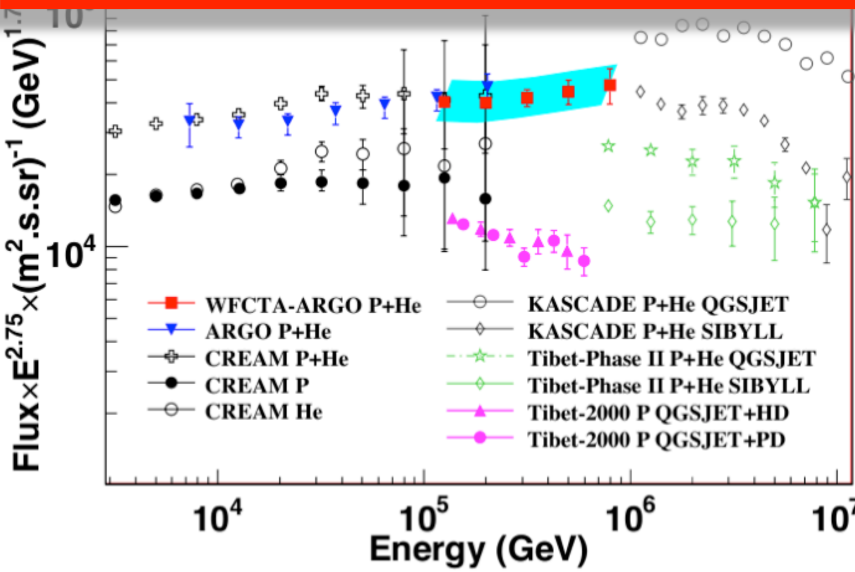


P+HE SPECTRUM (Kascade)



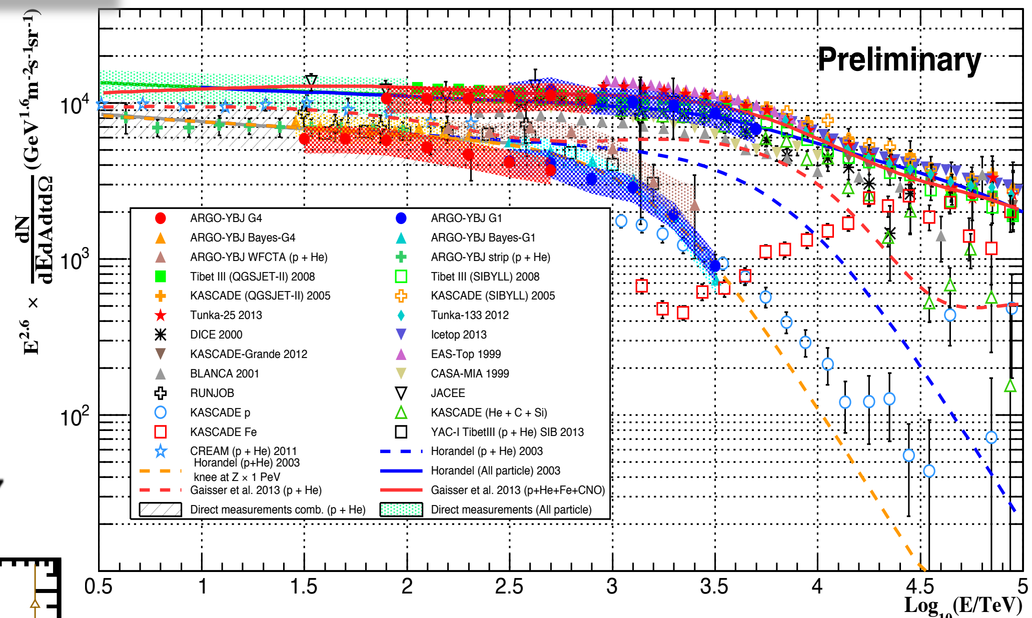
Some questions on CR

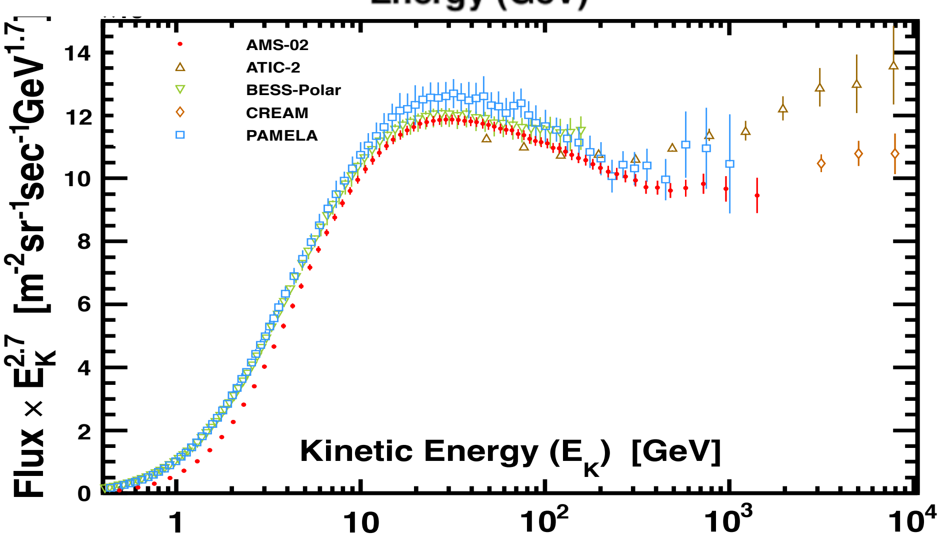
✓ Spectral behaviors and relative abundances p,He



✓ Uncertainty in the knee position of p and He

$$E_{max}(Z) = Z E^{p}_{max}$$



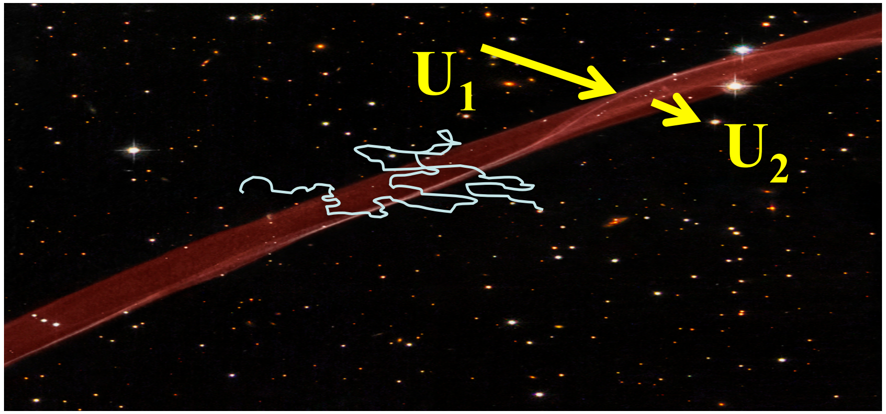


✓ Hadronic interaction models in ground based experiments seem the largest source of uncertainty.

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

✓ Presence of spectral brakes

Diffusive Shock Acceleration



Maximum Energy

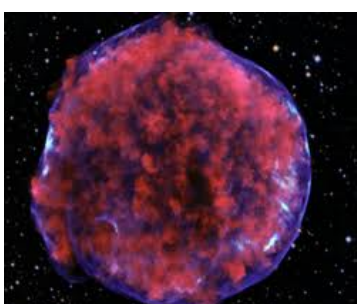
$$\tau_{diff} = \frac{D(E)}{V_{sh}^2} \leq \mathrm{Min}(\tau_{SNR}, \tau_{loss}, \tau_{esc})$$

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

X-rays observations

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

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

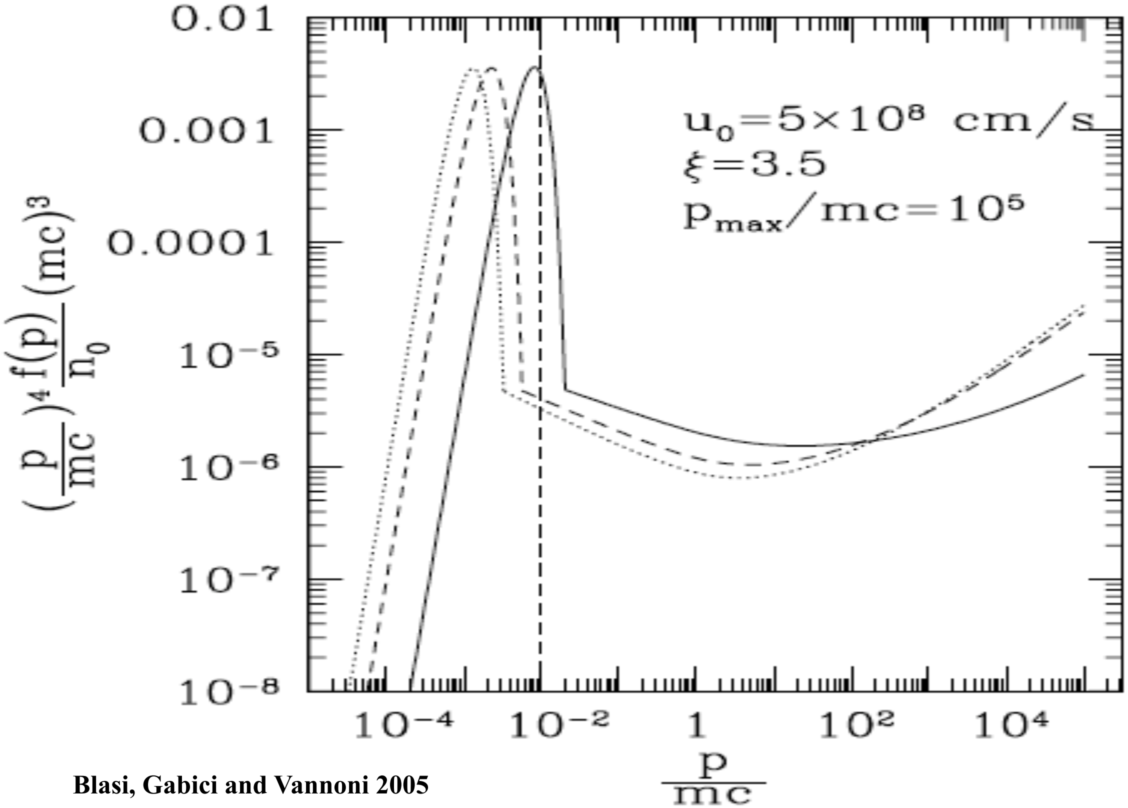


Comparison with the observed thickness leads to a B-field estimate

$$B \simeq 100 \mu G$$

- ✓ 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 reach $E_{max} \sim 10^5$-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.

Non Linear DSA



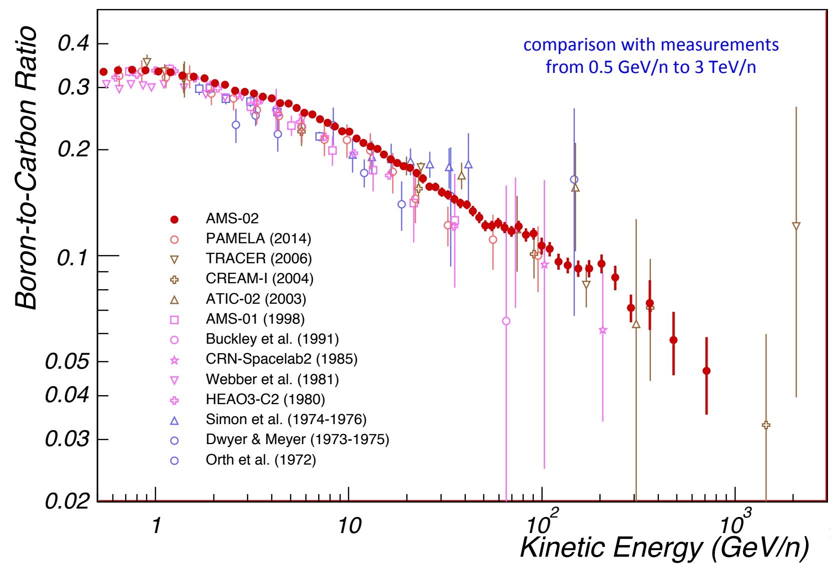
Blasi, Gabici and Vannoni 2005

- ✓ Compression factor becomes function of energy.
- ✓ Accelerated spectra are not perfect power laws (concave).
- ✓ Gas beyond the shock is cooler for efficient shock acceleration.
- ✓ System is self regulated.
- ✓ Efficient growth of B-field if acceleration in efficient.

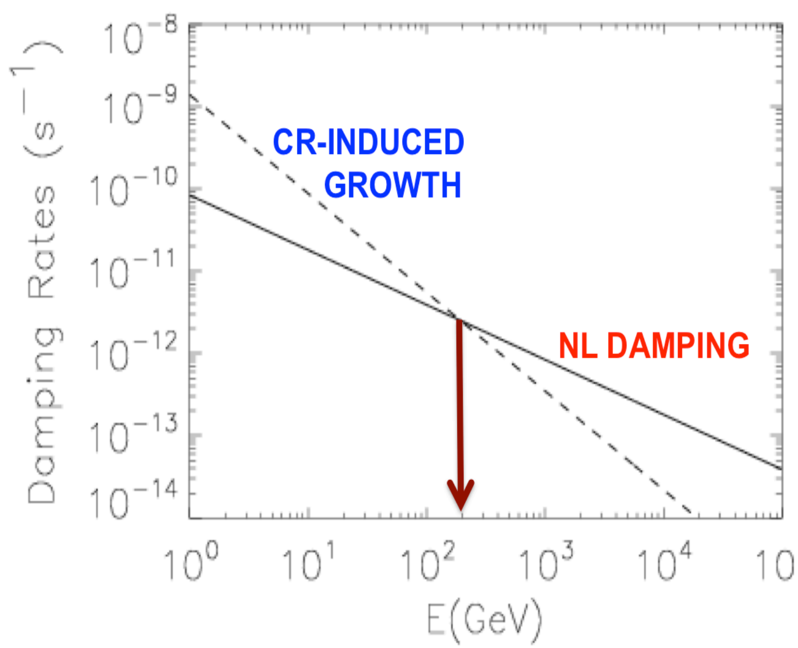
CR Propagation and self generated turbulence

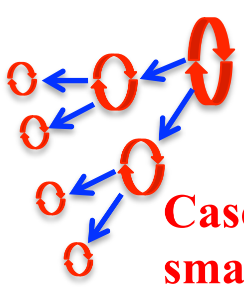
The decrease of B/C with energy/nucleon is the best sign of a rigidity dependent grammage traversed by CR on their way out of the galaxy. It confirms the picture of a diffusive propagation of CR

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

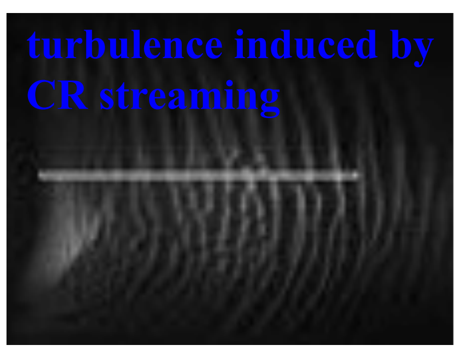


CR may excite a streaming instability when their motion is super-alfvenic. Self generated turbulence together with pre-existing one, injected by SN and cascading to smaller scales, produces the conditions for CR diffusion in a non-linear self regulating way.



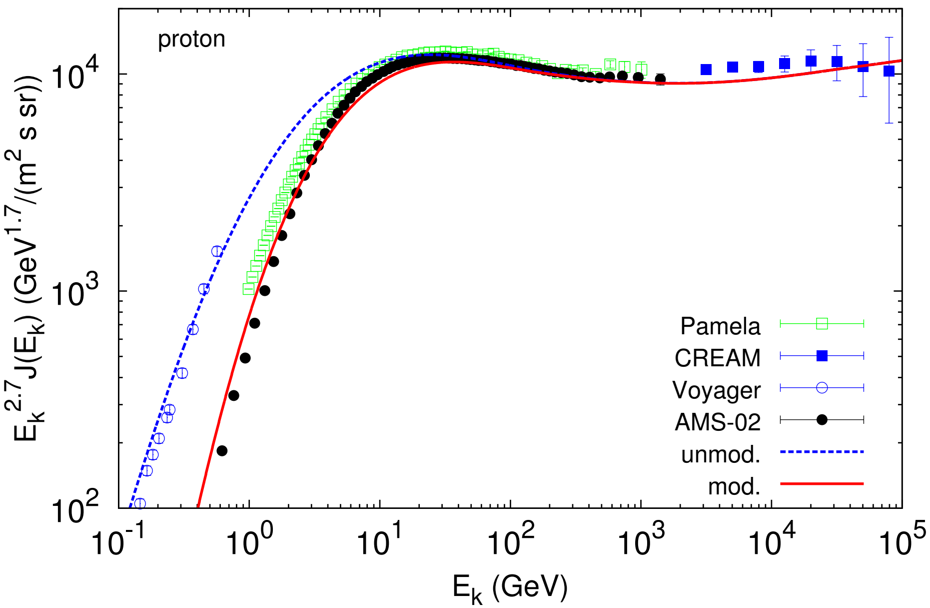


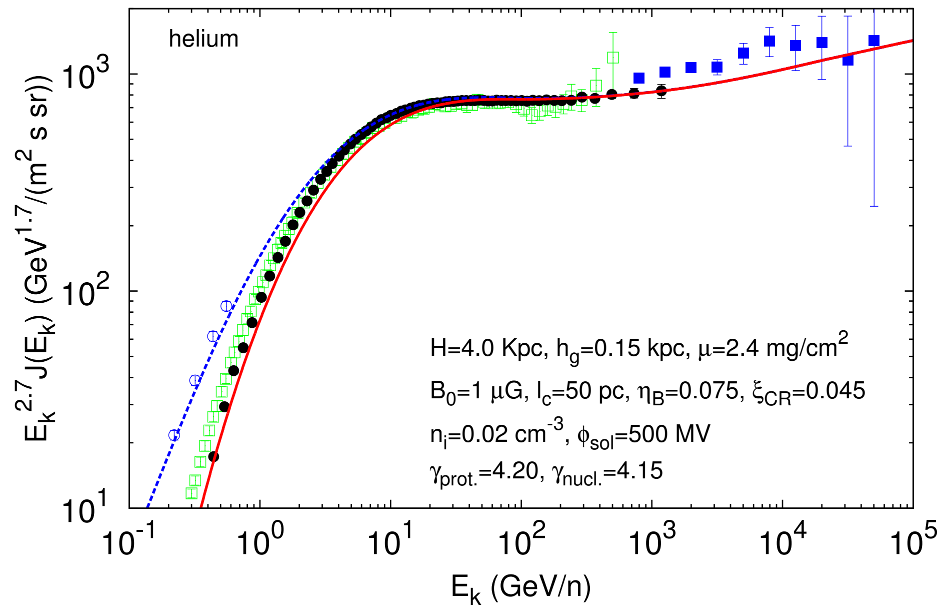
Cascading to smaller scales

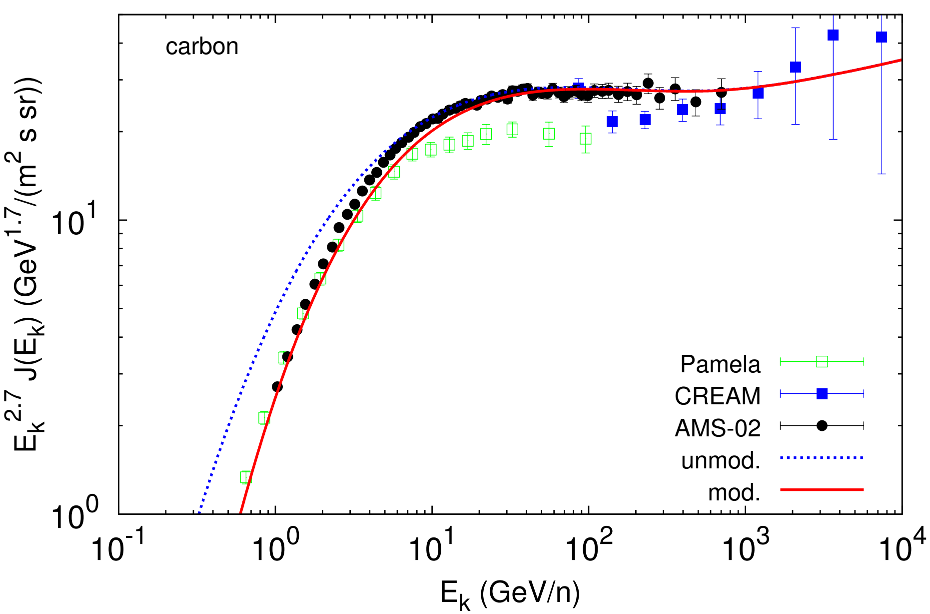


AMS-02 and Voyager

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

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

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

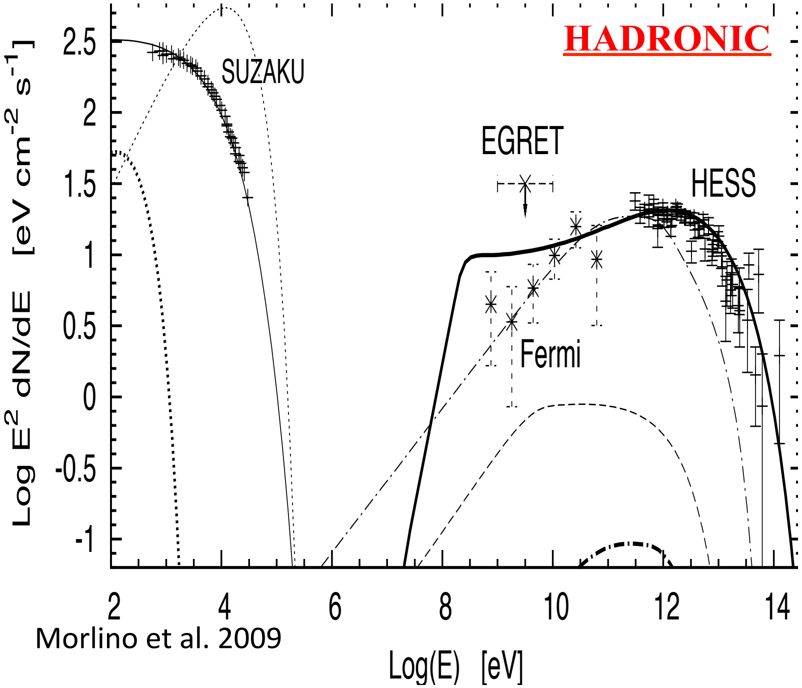
Leptonic models

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

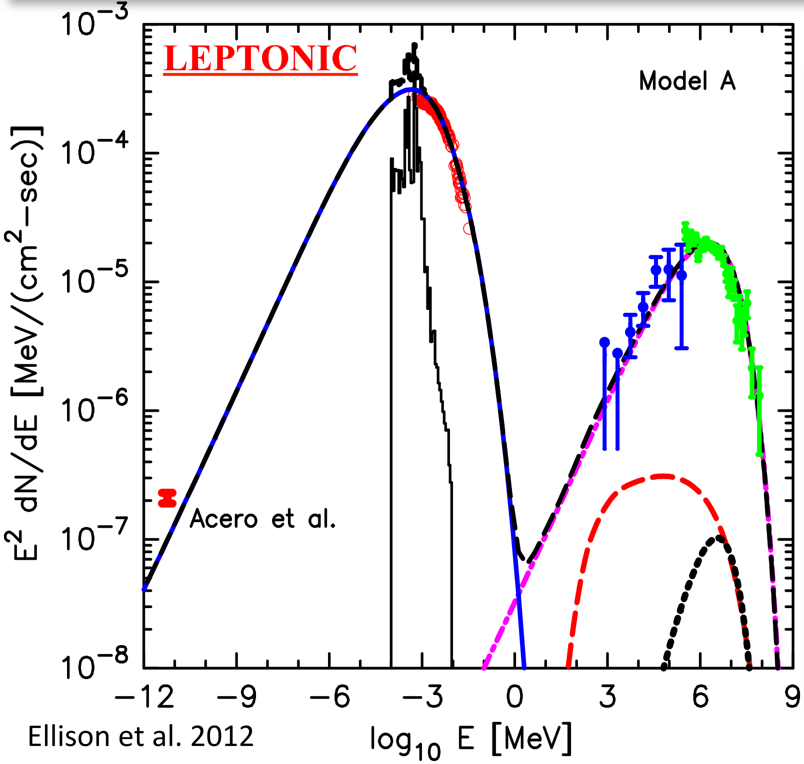
$$E^{-(\gamma+1)/2}$$

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



Morlino et al. 2009

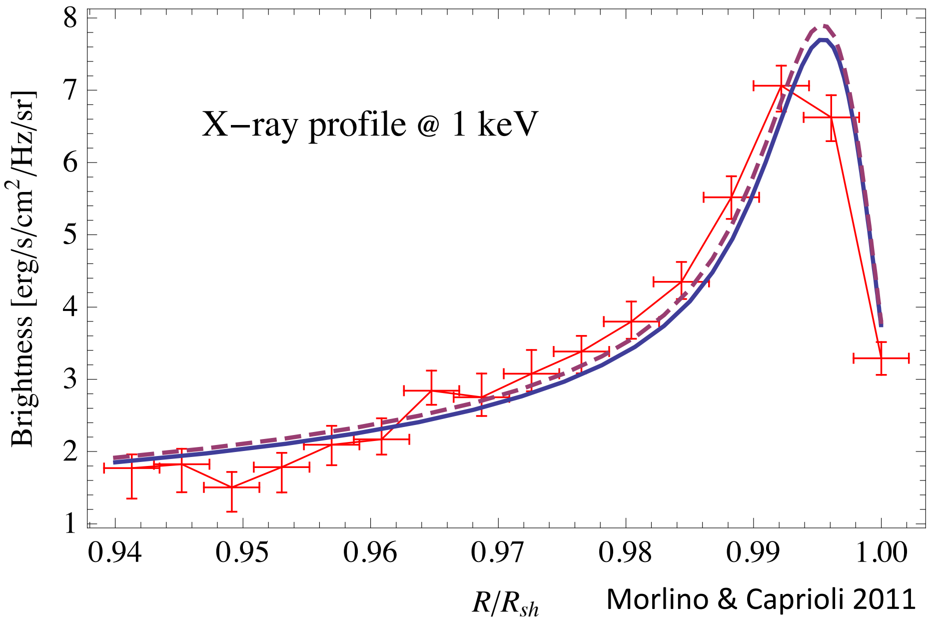


Ellison et al. 2012

- ✓ No oxygen lines observed, very small target 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.

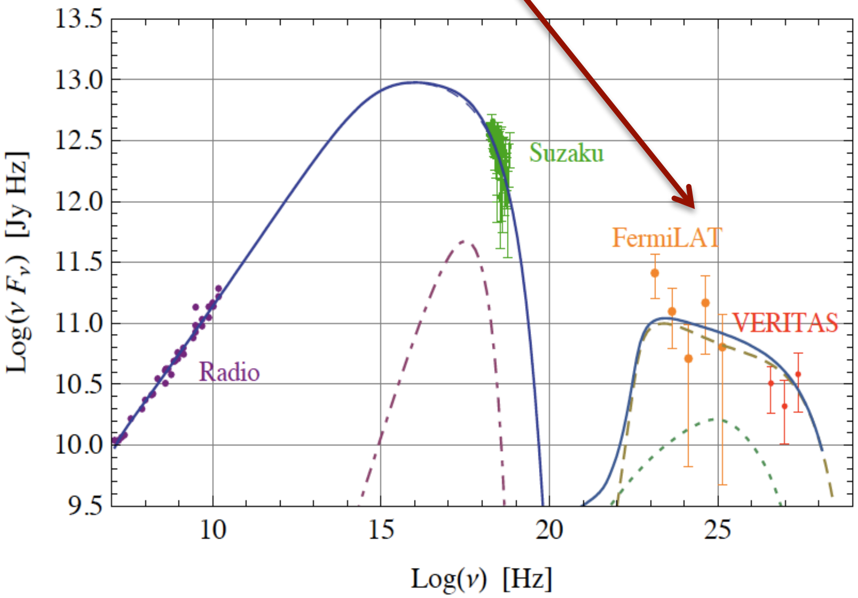
The case of Tycho

- ✓ 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

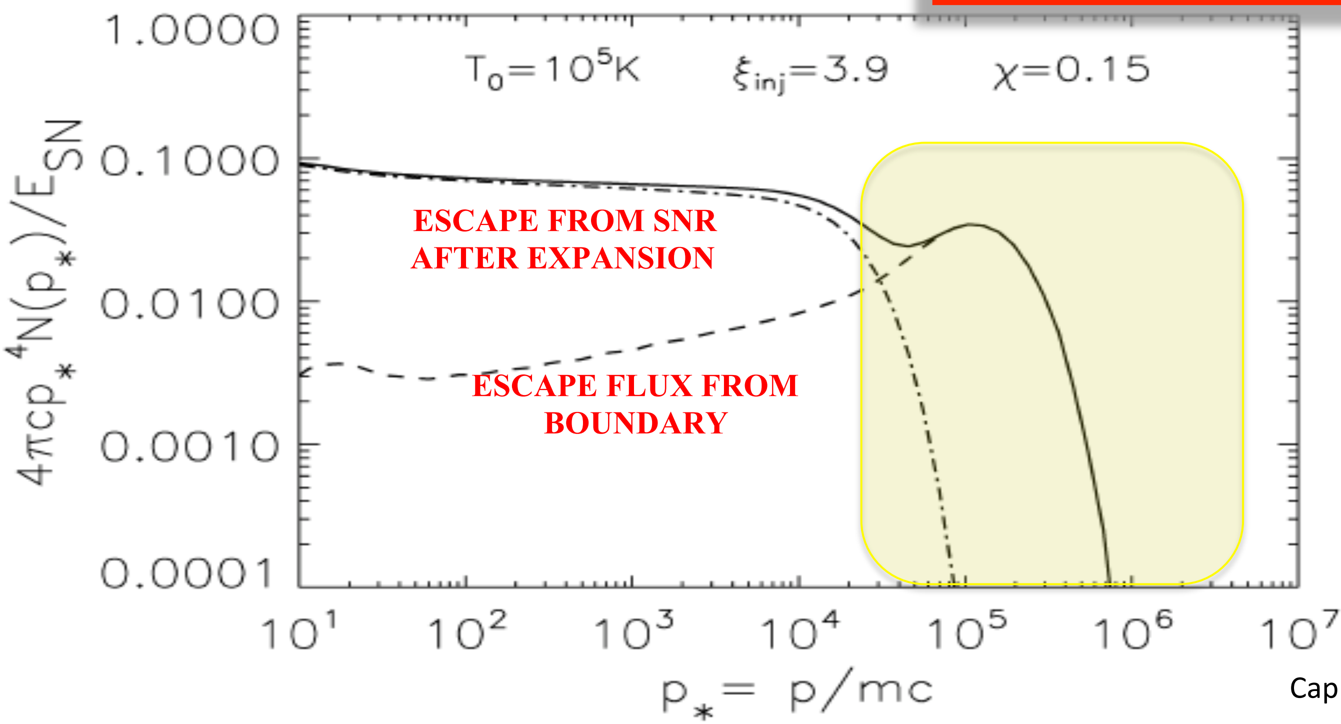
- The pion peak has not been seen so far (only in molecular clouds this feature seems observed, see later)

- 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})

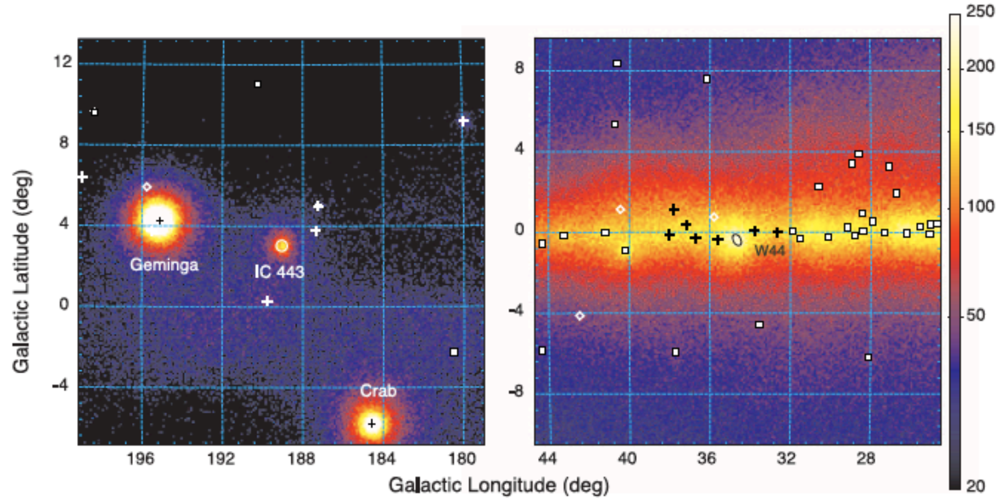
✓ particles released in the ISM after expansion

γ ray emission from molecular clouds

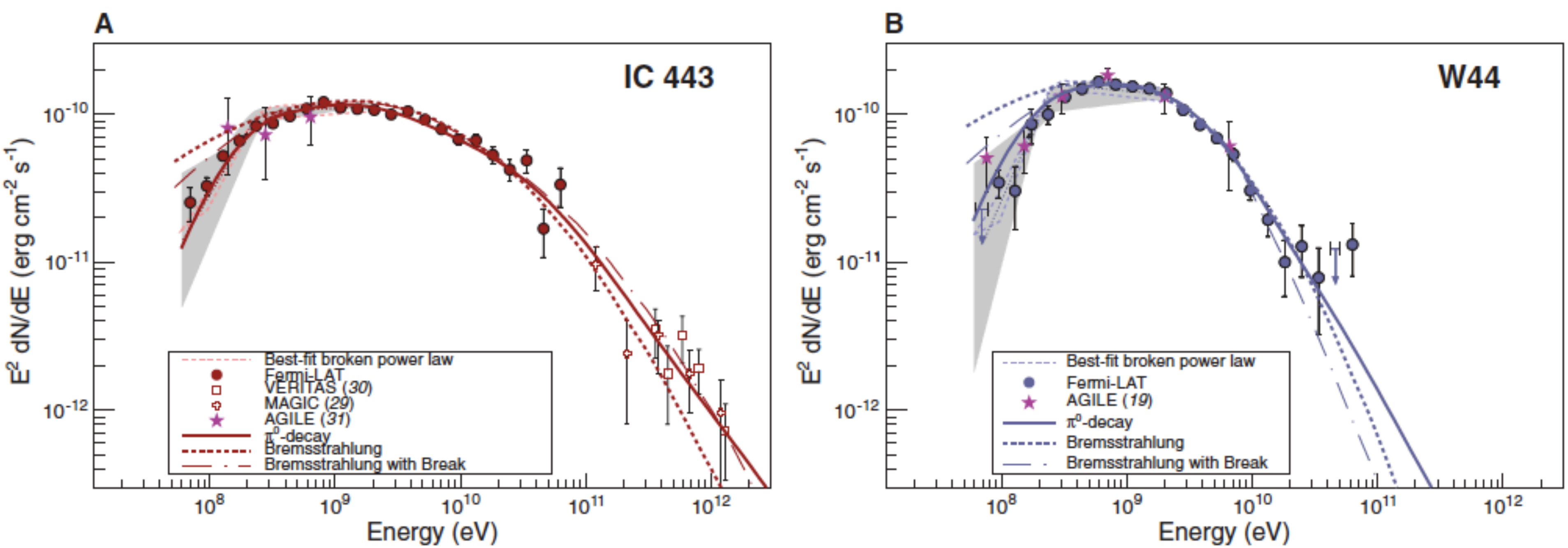
- ✓ Firm observation of the pion bump

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

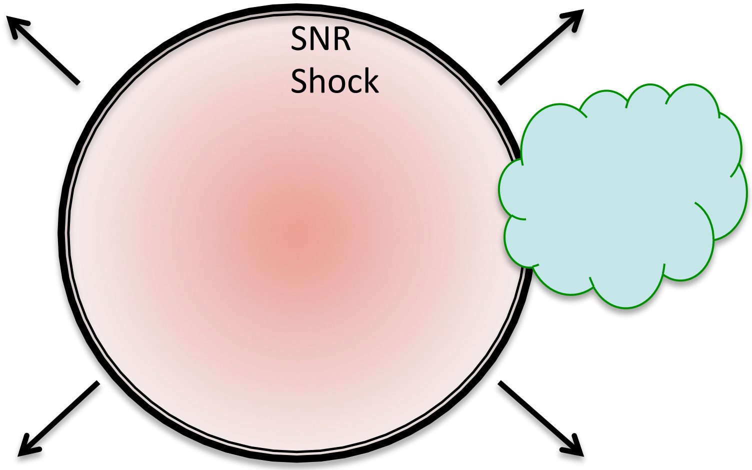
- ✓ SN close to molecular clouds are very interesting laboratories to investigate CR propagation around sources and escape from sources.



Ackermann et al. 2013

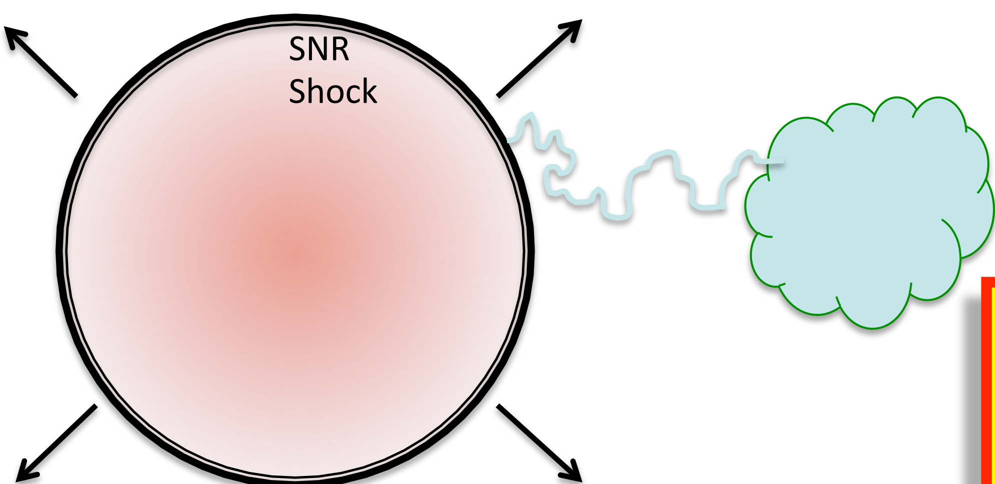


Shock inside the cloud



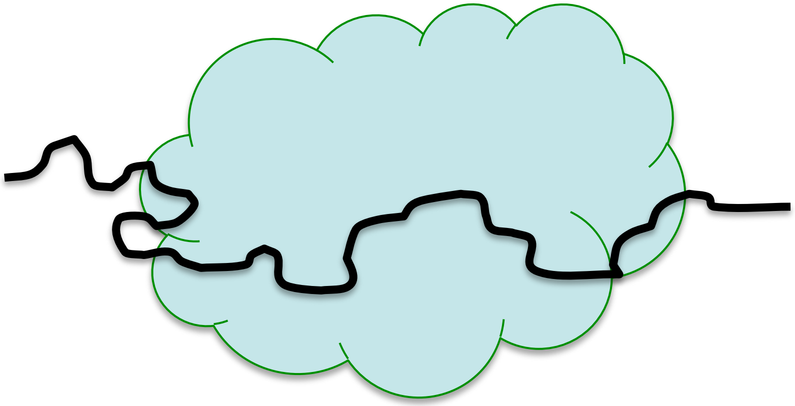
- ✓ the shock becomes collisional on scales
  $$\lambda \approx \frac{1}{n_{cloud}\sigma_{mol}} \sim 10^{10}\left(\frac{n_{cloud}}{10^4 cm^{-3}}\right)^{-1}\left(\frac{\sigma_{mol}}{10^{-14} cm^2}\right)^{-1} cm$$
- ✓ It slows down since it feels the matter in the cloud, particle already accelerated escape streaming away and interacting with matter in the molecular cloud.

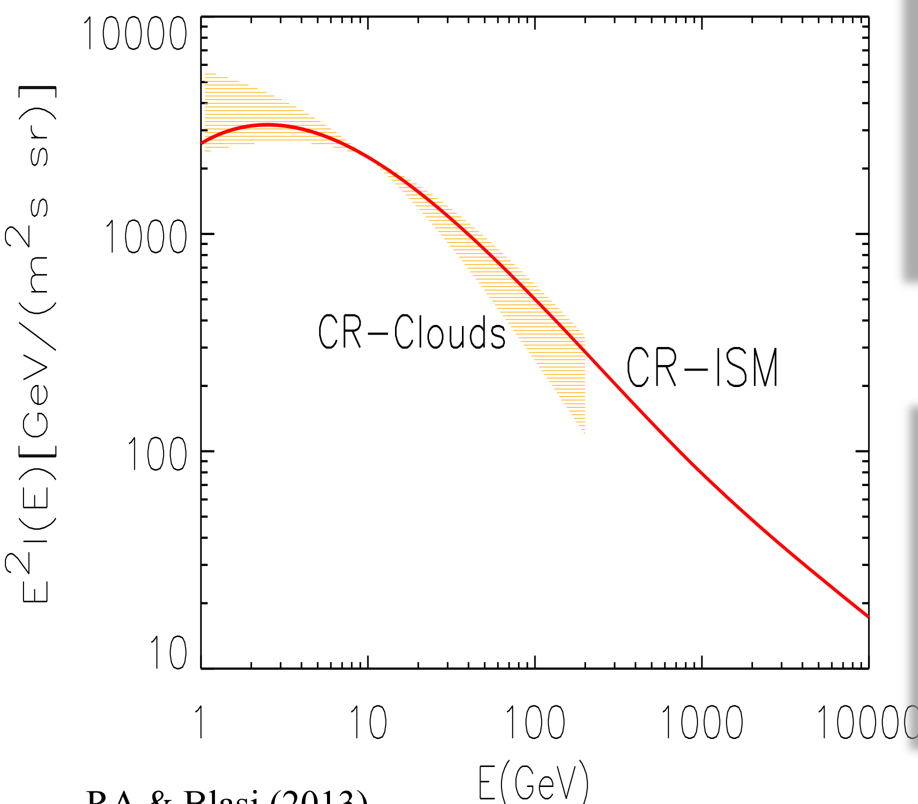
Shock outside the cloud



- ✓ 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 a 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, detected by Fermi (and by COS-B and EGRET in the past), 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.

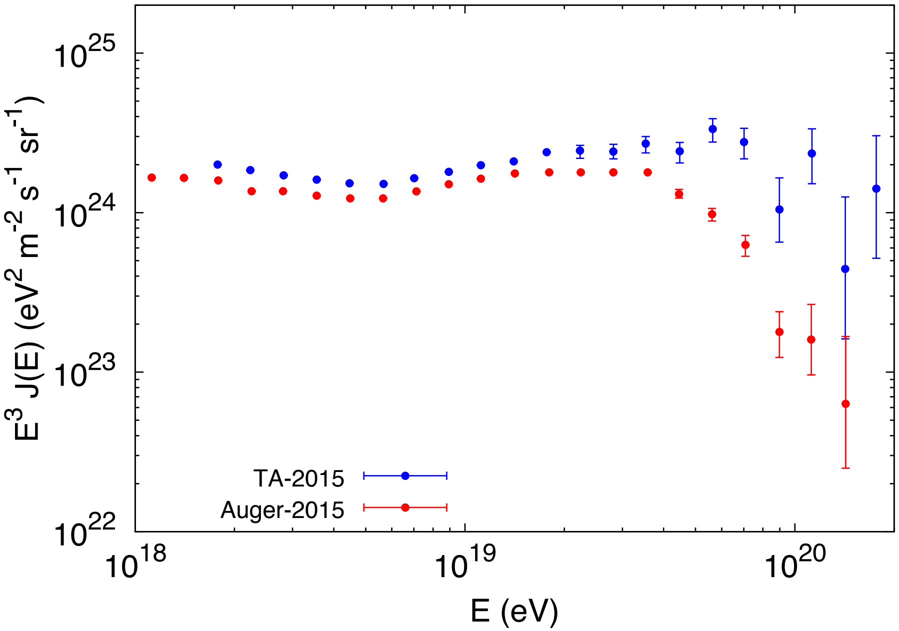
γ rays from molecular clouds – quick summary

- ✓ 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.

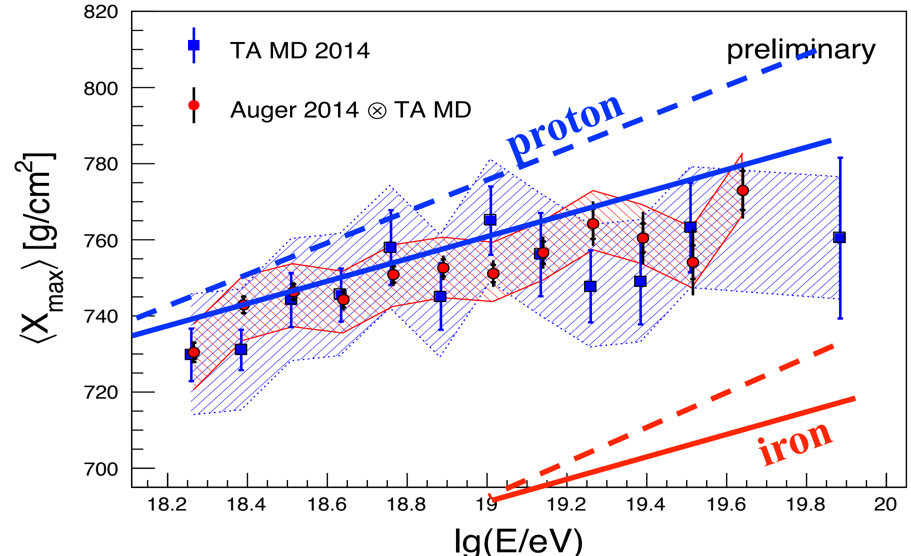
- ✓ The two contributions to the injected spectrum (i.e. from escaped particles and particles released after the end of expansion) can be disentangled looking at the gamma ray emission from clouds.

- ✓ 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.

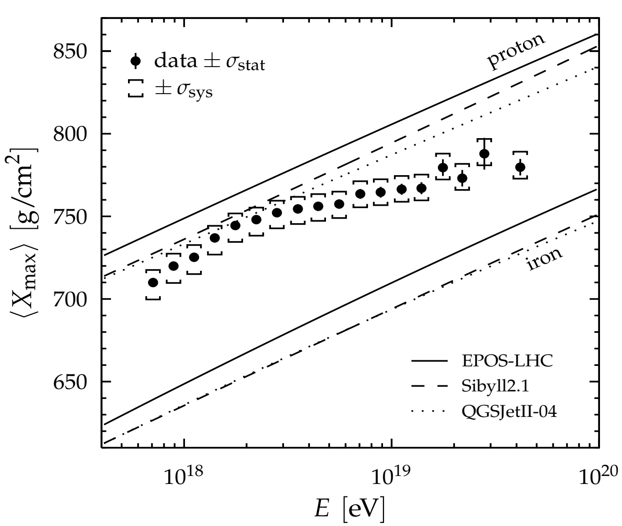
CR at Ultra High Energies

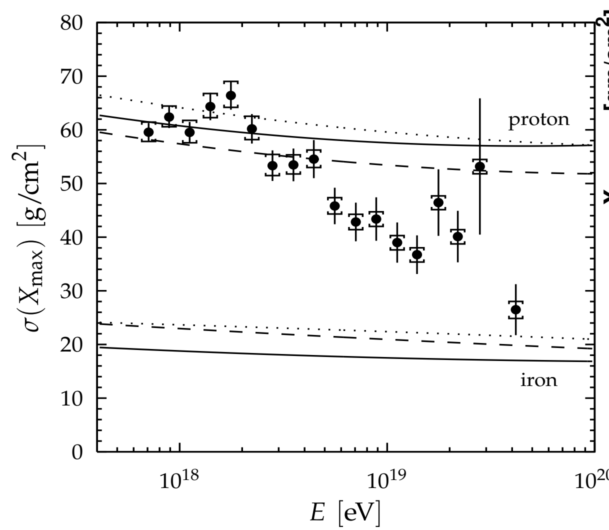


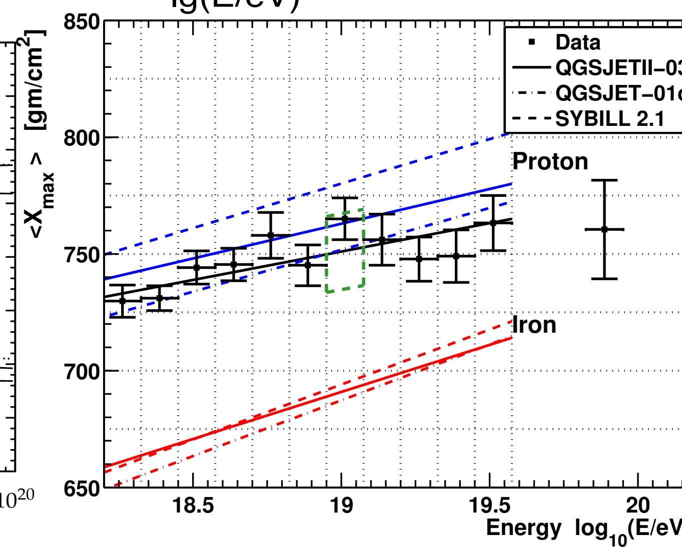
✓ TA points toward a pure proton composition at all energies.



✓ Auger observes an increasing heavy composition at the highest energies



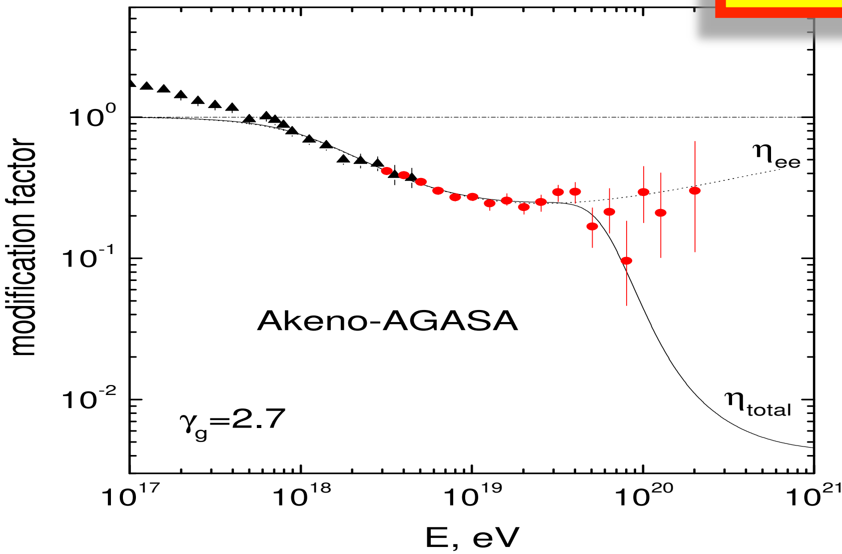


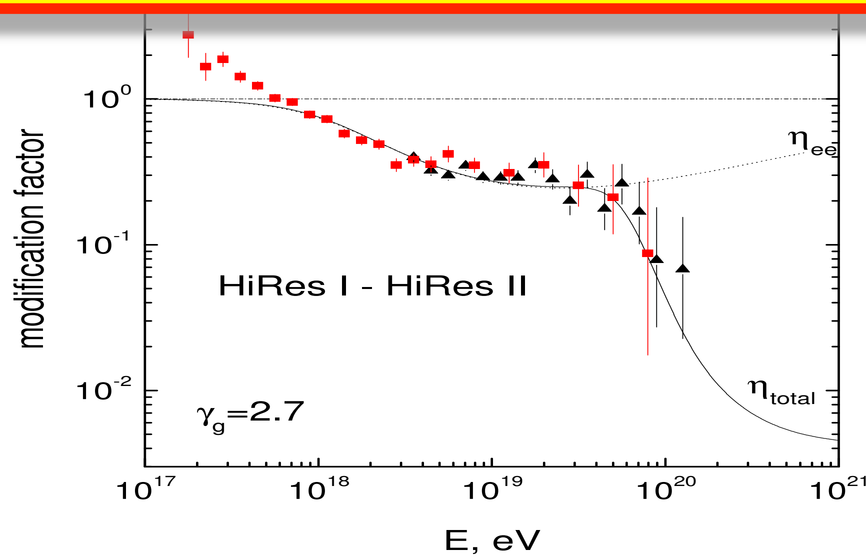


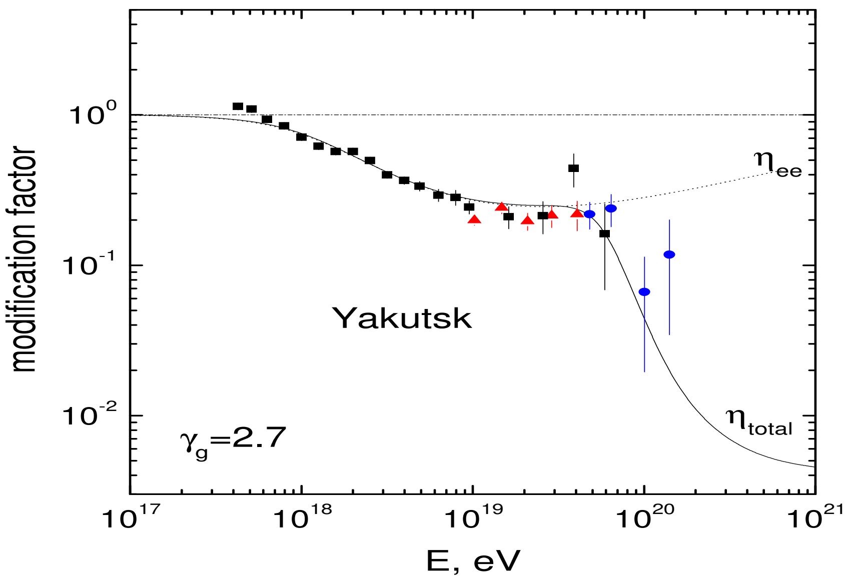
Dip Model

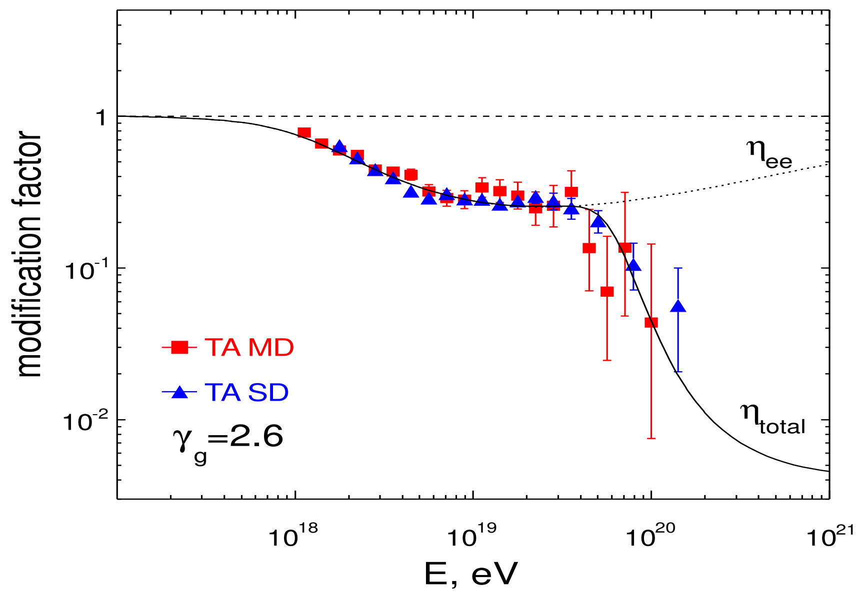
the protons footprint

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.



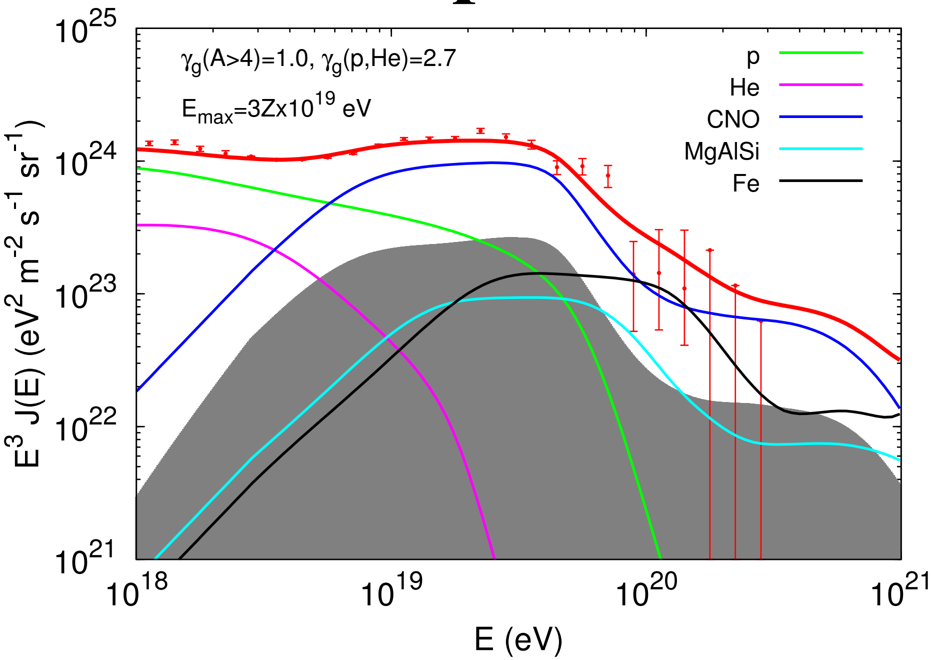






Berezinsky et al (2002) - RA et al. (2007-2012)

Mixed Composition



Two types of extra-galactic sources:

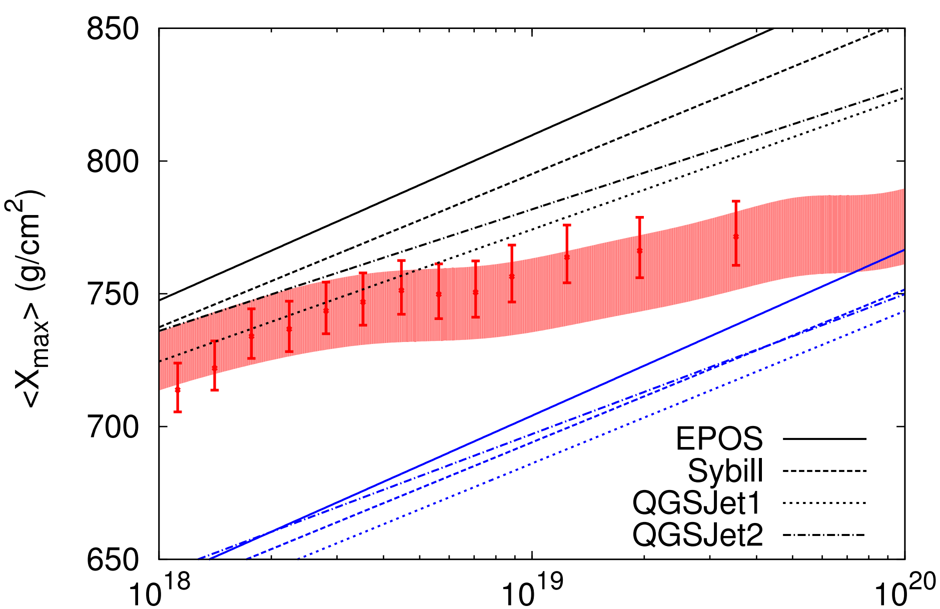
- ✓ light component steep injection (γ_g>2.5)

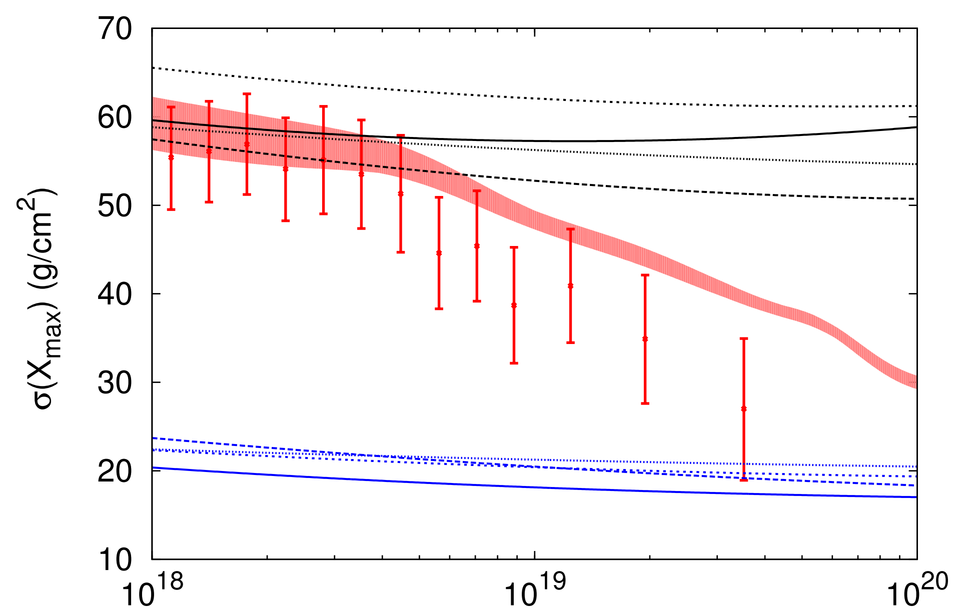
$$\mathcal{L}_0 = n_{UHE} L_{UHE} \simeq 10^{47} \frac{\text{erg}}{\text{Mpc}^3\text{y}}$$

- ✓ 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



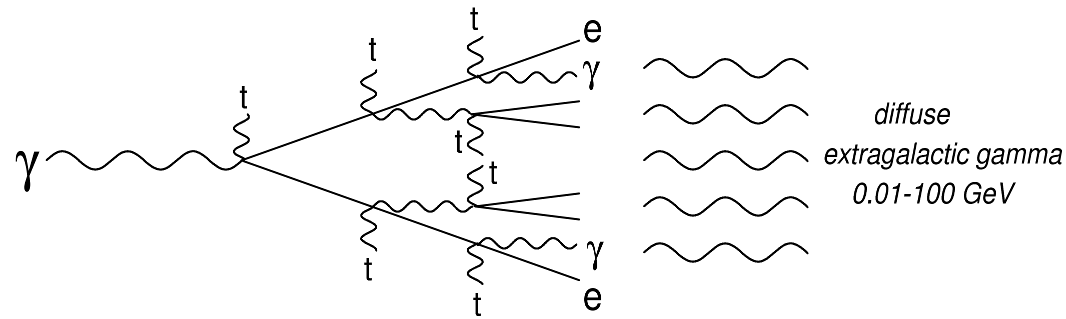


RA, Blasi, Berezinsky (2013); RA et al (2015)

Production of secondary γ

Cascade upper limit

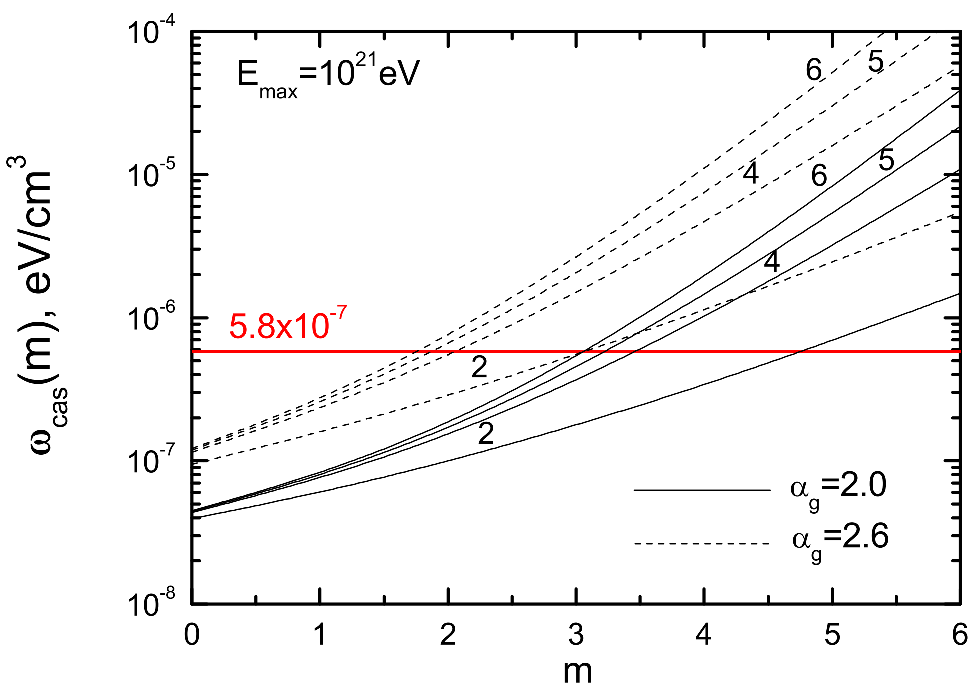
$$p\gamma \rightarrow e^{\pm}$$
$$p\gamma \rightarrow \pi^0 \rightarrow \gamma$$
$$p\gamma \rightarrow \pi^{\pm} \rightarrow e^{\pm}, \nu$$



Fermi-LAT data

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

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



Berezinsky, Gazizov, Kachelriess, Ostapchenko (2011)

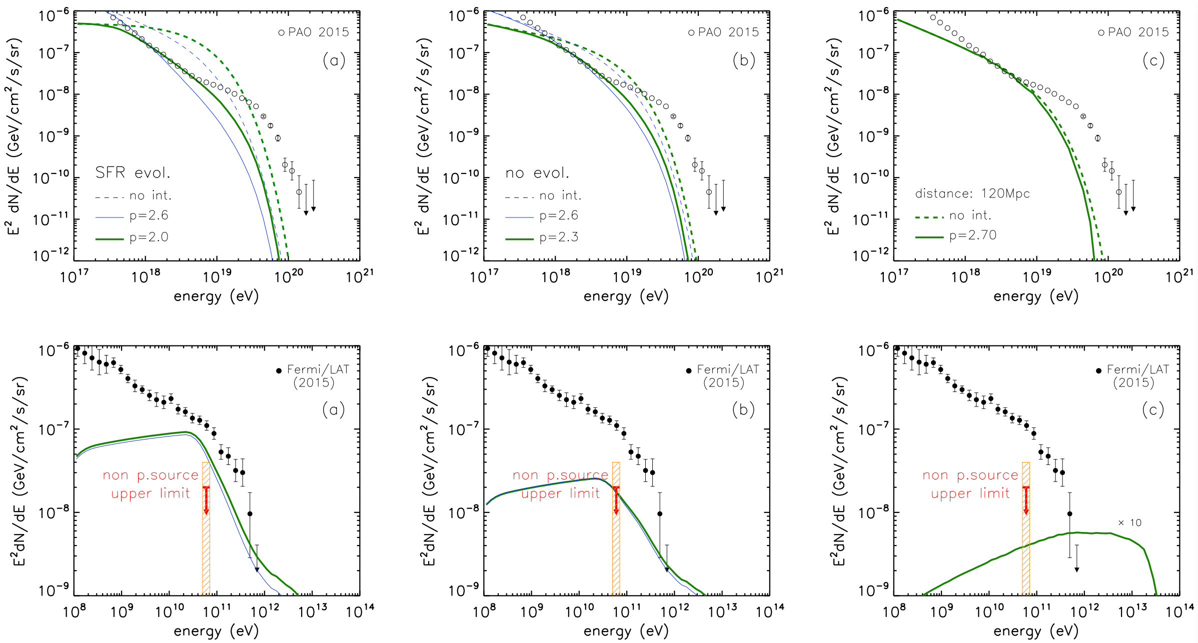
The cascade limit can be expressed in terms of the energy densities of photons and e$^+$e$^-$ initiated cascades

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

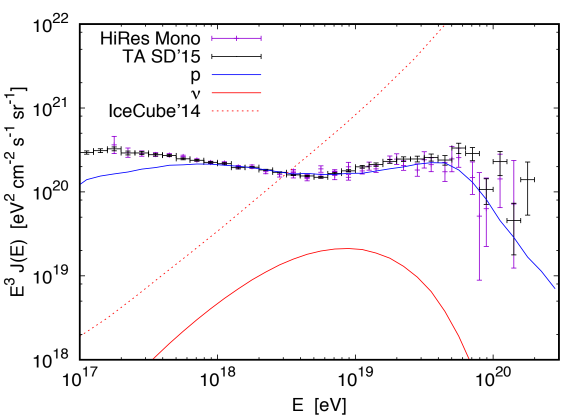
The cascade upper limit constrains the source parameters: <u>cosmological evolution, injection power law and maximum acceleration energy</u>.

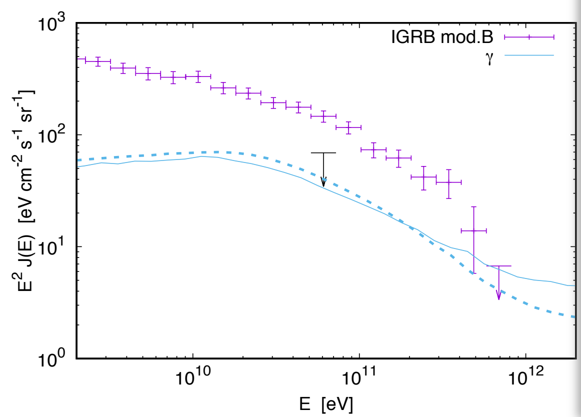
$$Q(E) = Q_0(1+z)^m \left(\frac{E}{E_0}\right)^{\alpha_g} e^{-E/E_{max}}$$

Diffuse gamma rays flux



Liu, Taylor, Wang, Aharonian (2016)





Berezinsky, Gazizov, Kalashev (2016)

- ✓ Diffuse extragalactic gamma-rays flux at E ~ 1 TeV is a very powerful observable to constrain the fraction of protons in the UHECR spectrum. With the available statistics, given the poor knowledge of the galactic diffuse foregrounds and EBL, it is impossible to exclude a pure proton composition at (1 − 40) EeV.
- ✓ The observation of the diffuse extra-galactic gamma-ray background will be one of the important tasks for the future CTA observatory.

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 could solve 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.

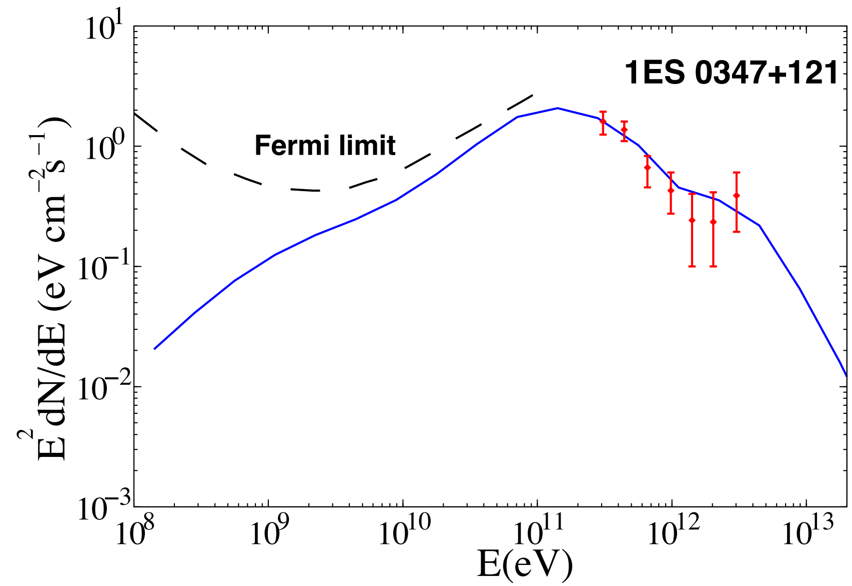
Ferrigno, Blasi, De Marco (2004)

Essey, Kalashev, Kusenko, Beacom (2009-13)

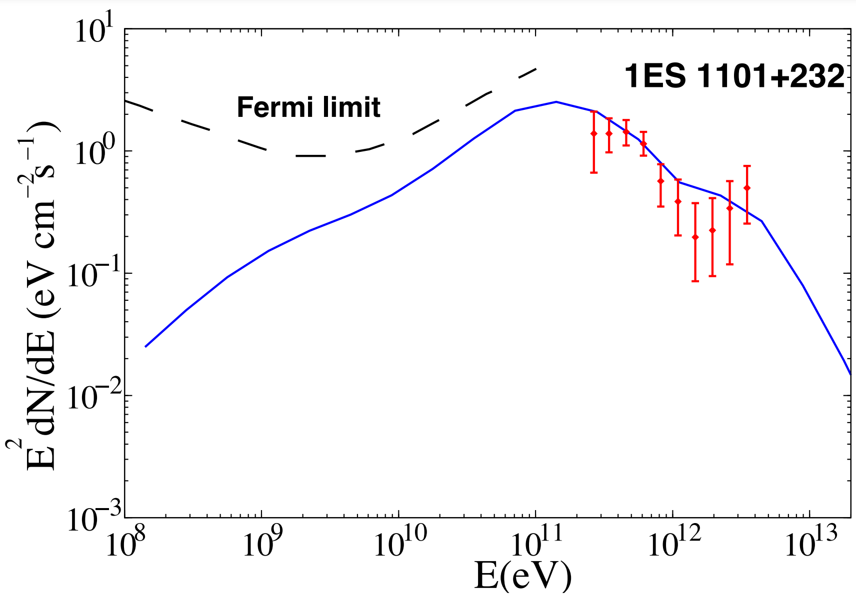
gamma rays (HESS)

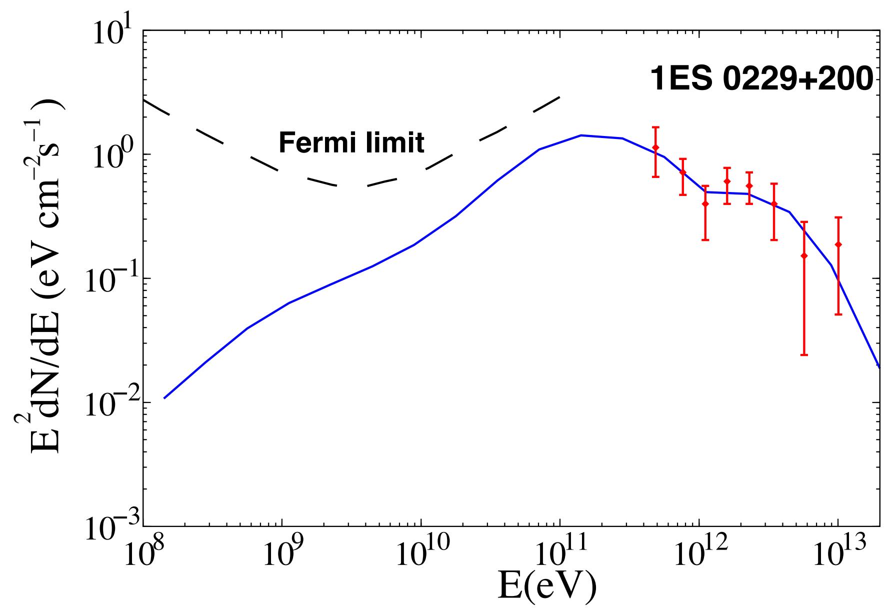
The shape of the spectrum is fixed by the EBL, the overall height is proportional to the product of UHECR luminosity and the level of EBL.

The effect of different E_{max} is to change the relative contribution of the different backgrounds 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)





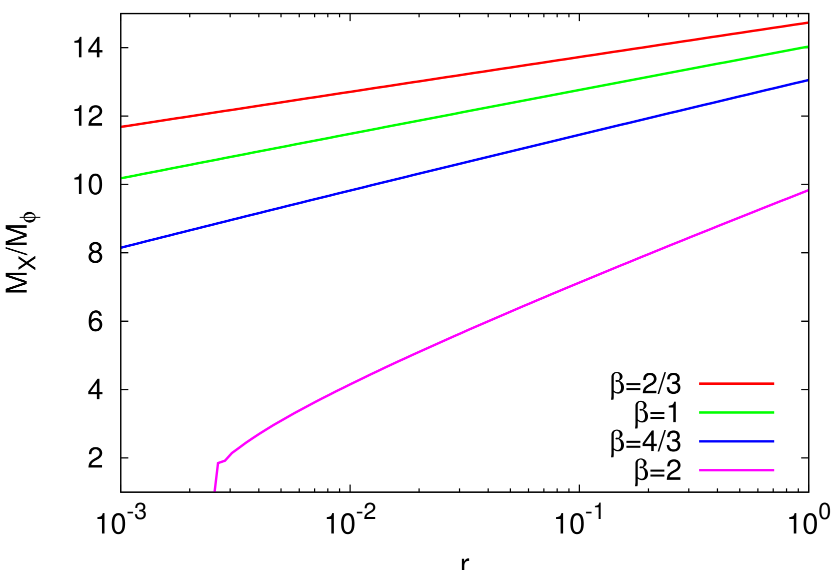
Extreme energies: Cosmology, DM & UHECR

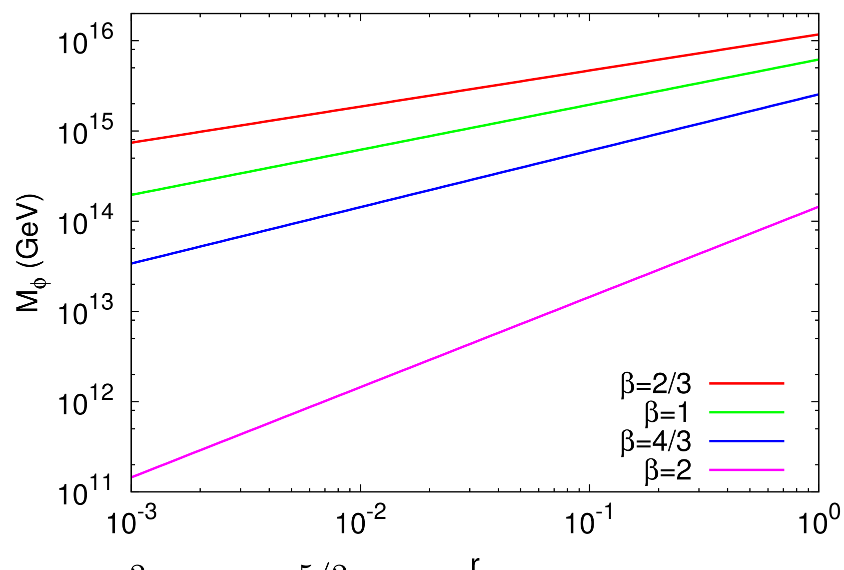
The tensor-to-scalar ratio (r) in CMB fluctuations sets the scale for models where the dark matter is created at the inflationary epoch, the generically called super-heavy dark matter models. These scenarios can be constrained by ultrahigh energy cosmic ray, gamma ray and neutrino observations which set the limit on super-heavy dark matter particles lifetime. Super-heavy dark matter can be discovered by a precise measurement of r combined with future observations of ultra high energy cosmic rays, gamma rays and neutrinos.

$$V(\phi) = \frac{M_\phi^{4-\beta}}{\beta}\phi^\beta \qquad V_\star \simeq \frac{3\pi^2}{2} A_s r M_{Pl}^4 \simeq M_{GUT}^4 \left(\frac{r}{r_0}\right)$$

$$\epsilon(\phi) = \frac{M_{Pl}^2}{16\pi}\left[\frac{V'(\phi)}{V(\phi)}\right]^2 = \frac{r}{16}$$

SHDM mass M_X determined assuming $\Omega_X = \Omega_{DM}$ today

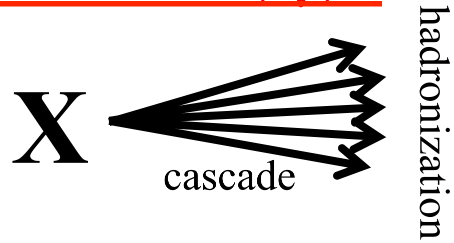




RA, Matarrese, Olinto (2015)

$$\Omega_X(t_0) \simeq 10^{-3}\Omega_R \frac{8\pi}{3}\left(\frac{T_{RH}}{T_0}\right)\left(\frac{M_\phi}{M_{Pl}}\right)^2\left(\frac{M_X}{M_\phi}\right)^{5/2} e^{-2M_X/M_\phi}$$

From SHDM to UHECR, γ, ν

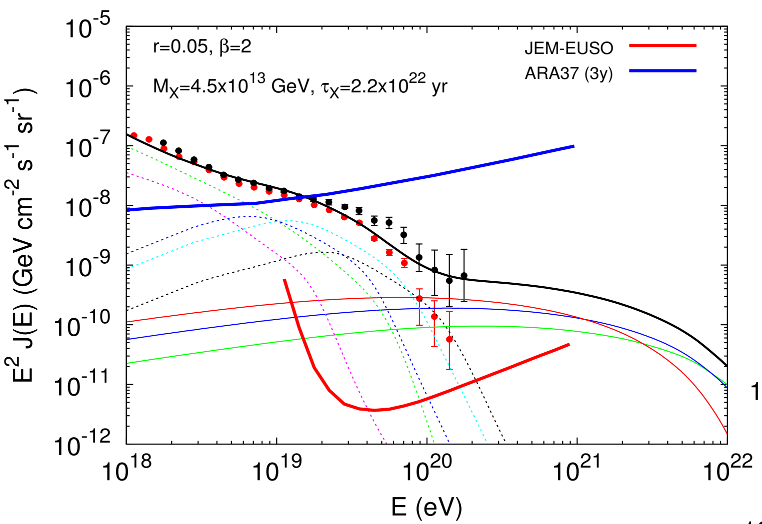


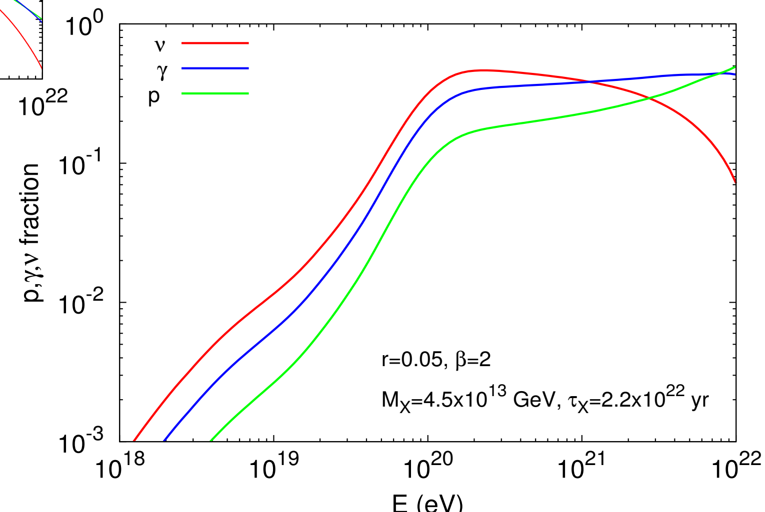
mainly π
therefore γ and ν

$$Q_{\nu,\gamma,p} \propto E^{-1.9}$$

- ✓ SHDM lifetime τ_X regulates the expected CR flux.
- ✓ SHDM halo with Moore density profile
- ✓ Integrating over the whole sky.
- ✓ Taking into account the whole universe.

$$J_{SHDM}(E,\theta) = \frac{1}{4\pi M_X \tau_X} Q(E) \int_0^{r_{max}(\theta)} dr\, n_X(R(r))$$





RA, Matarrese, Olinto (2015)

Conclusions

γ-rays (and ν see Lipari's talk) are of paramount importance in CR physics. Only a multiple messengers analysis can validate theoretical models.

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)

Galactic CR

- ✓ γ-rays extragalactic diffuse flux severely constrain models for UHECR composition, sources and their cosmological evolution.
- ✓ γ-rays from isolated AGN can be related to the UHECR produced in the AGN, giving a direct link with acceleration sites.
- ✓ γ-rays (and ν) at extreme energies ($E>10^{18}$ eV) can probe early universe and physics beyond the standard model.

ExtraGalactic CR