High Energy Radiation Processes II: Hadronic Processes

Roberto Aloisio

Gran Sasso Science Institute – L'Aquila (Italy)

INFN – Laboratori Nazionali Gran Sasso – L'Aquila (Italy)

GRAN SASSO SCIENCE INSTITUTE
SCHOOL OF ADVANCED STUDIES
Scuola Universitaria Superiore

INFN LNGS
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali del Gran Sasso

Plan of the lecture

1. Proton-proton interactions
   - 1.a Threshold for multi-particle production
   - 1.b Inelastic pp scattering, neutral pions and gamma rays
   - 1.c Gamma ray emissions in SNR and molecular clouds
   - 1.d Inelastic pp scattering, charged pions, muons and neutrinos

2. UHE Protons and nuclei interactions with background photons
   - 2.a Basic processes: pair production, photo-pion production, photo-disintegration
   - 2.b Transport in the extragalactic space – Protons and Nuclei
   - 2.c Secondary gamma rays, diffuse extragalactic background and distant AGN
   - 2.d Secondary neutrinos and ultra high energy cosmic rays composition

Basic bibliography

Books:

V.S. Berezinskii, S.V. Bulanov, V.A. Dogiel, V.L. Ginzburg, V.S. Ptuskin "Astrophysics of Cosmic Rays" North Holland, **ISBN-13:** 978-0444886415 **ISBN-10:** 0444886419.

T.K. Gaisser, R. Engels, E. Resconi "Cosmic Rays and Particle Physics", Cambridge University press, **ISBN-13:** 978-0521016469 **ISBN-10:** 0521016460.

F. Aharonian "Very High Energy Cosmic Radiation", World Scientific Publishing Co, **ISBN-13:** 978-9810245733 **ISBN-10:** 9810245734.

R. Aloisio, E. Coccia, F. Vissani (Eds.) "Multiple Messengers and Challenges in Astroparticle Physics", Springer Publishing Co, **ISBN-13:** 978-3319654232 **ISBN-10:** 3319654233.

Several relevant papers are cited in the text

Proton-Proton interactions

Threshold for multi-particle production

Let us start discussing the threshold for multi-particles production. Let us consider the generic process

$$a + b \to c + d + e + \ldots$$

The threshold for this process is defined as the energy of the primary particles needed to produce the final particles at rest in their Center of Mass (CoM) reference frame. Recalling that this two quantities are Lorentz invariant:

$$s = (p_a + p_b)^2 = (p_c + p_d + p_e + \ldots)^2$$
$$p_a \cdot p_b = E_a E_b - \vec{p}_a \cdot \vec{p}_b$$

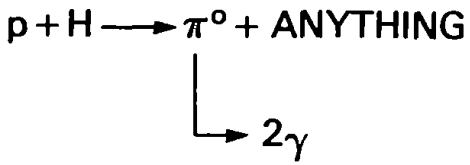
and imposing the threshold definition, being θ the scattering angle formed by the two initial particles momenta, one has

$$\begin{aligned} s_{th} = (p_a + p_b)^2 &= p_a \cdot p_a + p_b \cdot p_b + 2p_a \cdot p_b = \\ &= m_a^2 + m_b^2 + 2E_a E_b - 2\vec{p}_a \cdot \vec{p}_b = \\ &= (m_c + m_d + m_e + \ldots)^2 = \\ &= (m_a + m_b + \Delta m)^2 \end{aligned}$$

$$\begin{aligned} E_a E_b - \sqrt{E_a^2 - m_a^2}\sqrt{E_b^2 - m_b^2}\cos\theta = \\ = m_a m_b + \Delta m \left[m_a m_b + \frac{\Delta m}{2} \right] \end{aligned}$$

Neutral pion production

We discuss now the process of proton-proton interaction that gives rise to the production of neutral pions that in turn decay feeding the galactic gamma ray background. The process at hand is the interaction of cosmic rays protons with the protons of the interstellar medium that can be considered at rest and indicated with H



To fix the energetic scale of the problem let us start from the threshold for this reaction, that can be computed (using the definition) as the energy in the LAB frame of the incident proton needed to produce the final particles at rest in the CoM frame, i.e.

$$(E + m_p)^2 - p^2 = (M_{any} + m_\pi)^2 \quad \Rightarrow \quad E_{th}^{pp} = \frac{(M_{any} + m_\pi)^2 - 2m_\pi^2}{2m_p}$$

Being M_{any} the total rest mass of the final products apart from π^0 . The typical reaction of this kind implies the production of two protons in the final state in this case the threshold is:

$$p + H \rightarrow \pi^0 pp \qquad E_{th}^{pp} \simeq m_p + 2m_\pi$$

NOTE: Comparing the time scales for pp and diffusion it follows that the pp mechanism is irrelevant as energy losses mechanism for CR. Let us assume: constant pH cross-section σ_{pH}≈30 mb (3×10^{-26} cm^2), number density for protons in the ISM n_H=1 cm^{-3}, constant diffusion coefficient D=3×10^{28} cm^2/s, galactic halo and disk heights respectively H=3 Kpc and h=0.15 kpc.

Taking into account that the time spent in the disk is roughly h/H of the total diffusion time, one has

$$\tau_{pp} = \frac{H}{n_H hc\sigma_{pH}} \simeq 2 \times 10^{16}\mathrm{s} \qquad \tau_{diff} = \frac{H^2}{D} \simeq 2 \times 10^{15}\mathrm{s}$$

NOTE: pH interactions are important for the production of secondary gamma rays. Apart from the disk, pp is important in those regions with increased target density (and/or protons density) such as in molecular clouds or SNR.

The number of π^0 produced per unit volume, energy and steradiant (emission function or emissivity) can be computed as

$$J_\pi(E_\pi) = 4\pi n_H \int_{E_\pi}^{\infty} dE_p \; I_p(E_p) \frac{d\sigma(E_\pi, E_p)}{dE_\pi}$$

where I_p is the flux of CR protons and $d\sigma/dE_\pi$ is the differential cross section for the production of a π^0 with energy E_π in the LAB frame.

NOTE: Eq. above holds in the case of an isotropic distribution of both bullets and targets.

The emissivity J of secondary photons produced by the decay of pions is

$$J_\gamma(\epsilon_\gamma) = 2 \int_{\epsilon_\gamma + m_\pi^2/4\epsilon_\gamma}^{\infty} dE_\pi \frac{J_\pi(E_\pi)}{\sqrt{E_\pi^2 - m_\pi^2}}$$

and the minimum pion energy

$$E_\pi^{min} = \epsilon_\gamma + \frac{m_\pi^2}{4\epsilon_\gamma}$$

Using the spectrum of the final gamma rays given by:

$$\frac{dN}{dE_\gamma} = \frac{2}{|\vec{p}_\pi|} = \frac{2}{\sqrt{E_\pi^2 - m_\pi}}$$

The cross section for π^0 production from p+p interactions can be written in terms of the total inclusive cross section associated to the reaction pp → π^0 + anything, it is given by

$$\frac{d\sigma(E_p, E_\pi)}{dE_\pi} = \sigma_{inc}(E_p)\frac{f(E_p, E_\pi)}{E_\pi}$$

The quantity f is an auxiliary function that, fitted on the experimental data, should fulfill the condition

$$\int \frac{dE_\pi}{E_\pi} f(E_p, E_\pi) = 1$$

$$f(E_p, E_\pi) = f\left(\frac{E_\pi}{E_p}\right) = f(x) = 0.5[1.22(1-x)^{3.5} + 0.92\exp(-18x)]$$

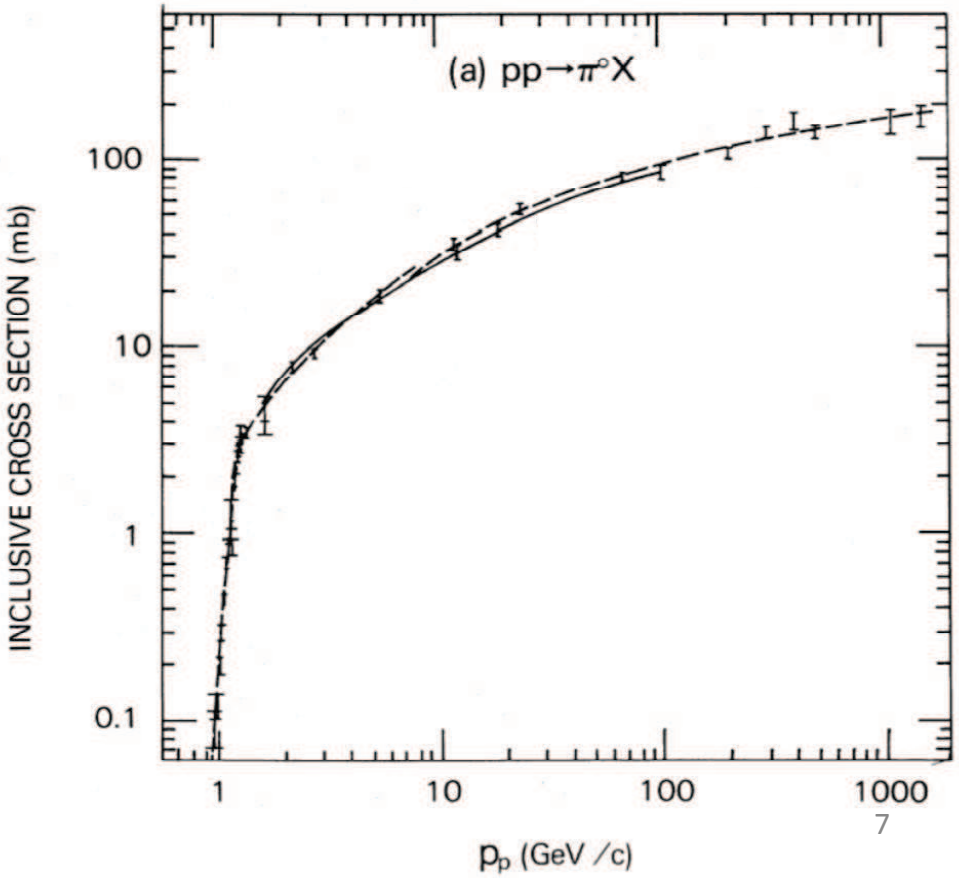
$$\sigma_{inc}(E_p) = 31 + 0.37\ln^2\left(\frac{E_p}{50GeV}\right) \quad \text{mb}$$

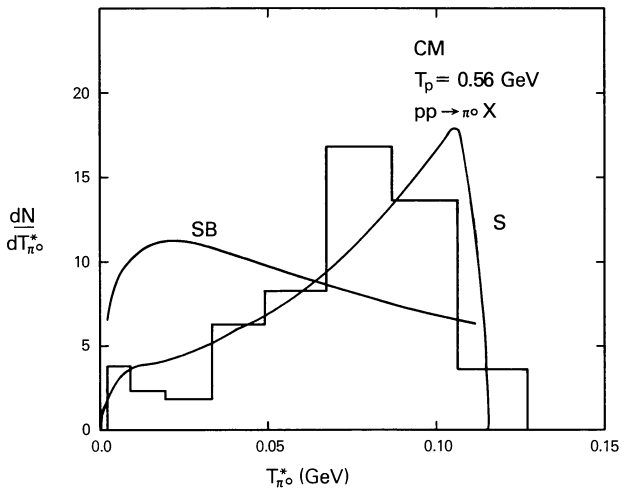
<u>Low energies</u>

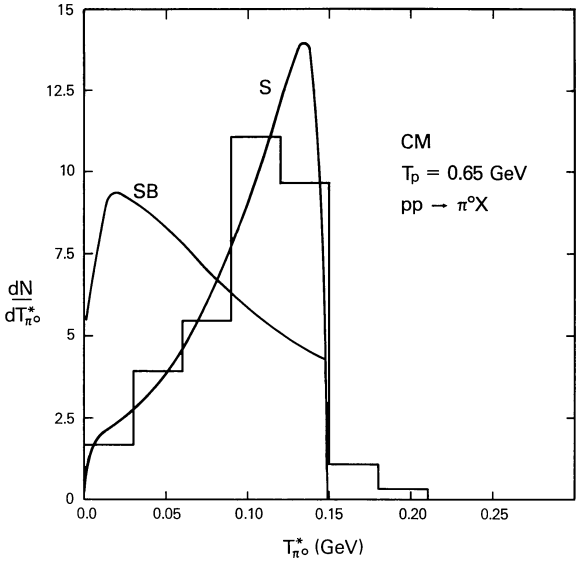
Near the pion production threshold at energies around 1 GeV the behavior of the cross section is model dependent, it suffers large experimental uncertainties.

<u>High energies</u>

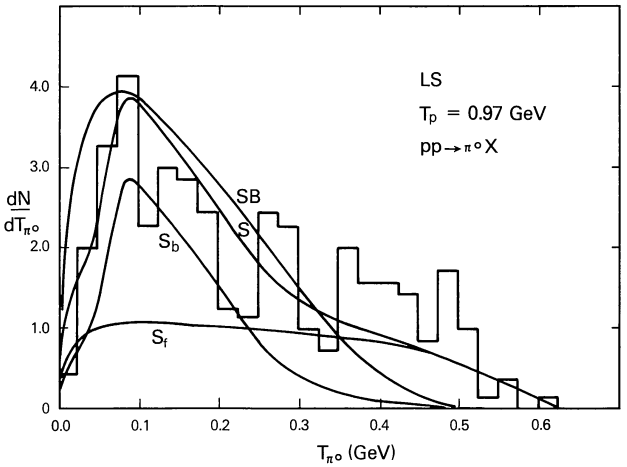
At energies larger than 10 GeV the behavior of the cross section is better understood with an almost constant (logarithmic) behavior and the function f satisfies the scaling f=f(x) with $x=E_\pi/E_p$.







Dermer 1986



Comparison of the model prediction of the function $f(E_\pi, E_p)/E_\pi$ with experimental data. Photons and pions emissivity (C.D. Dermer, A&A (1986)).

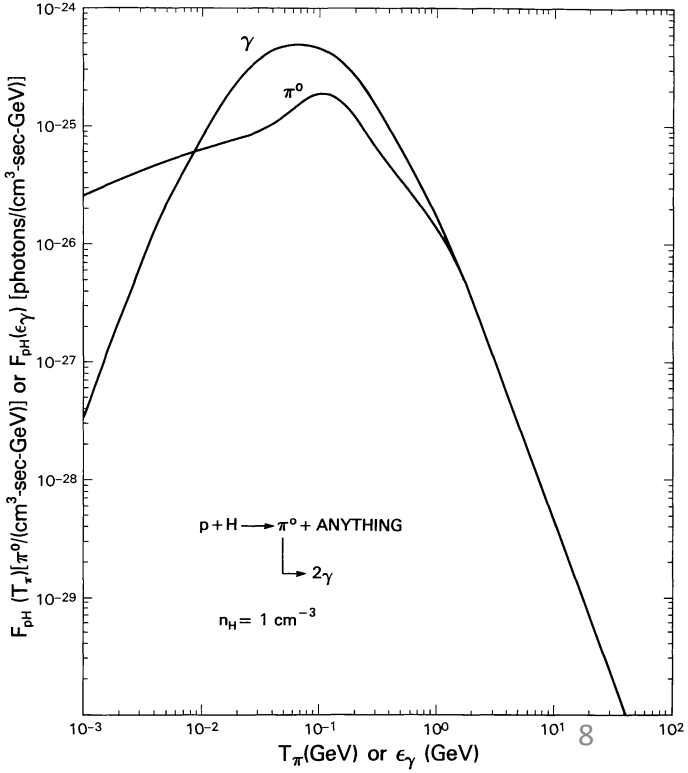
NOTE: If the CR spectrum as a power law behavior, the same behavior will be reproduced by pions and gamma rays:

$$I_p(E) = I_0 \left(\frac{E}{E_0}\right)^{-\gamma}$$

$$J_\pi(E_\pi) = 4\pi n_H I_0 E_0^\gamma E_\pi^{-\gamma} \sigma_0 \int_0^1 x^{\gamma-2} f(x) = 4\pi n_H \sigma_0 I_p(E_\pi) \Lambda_\gamma$$

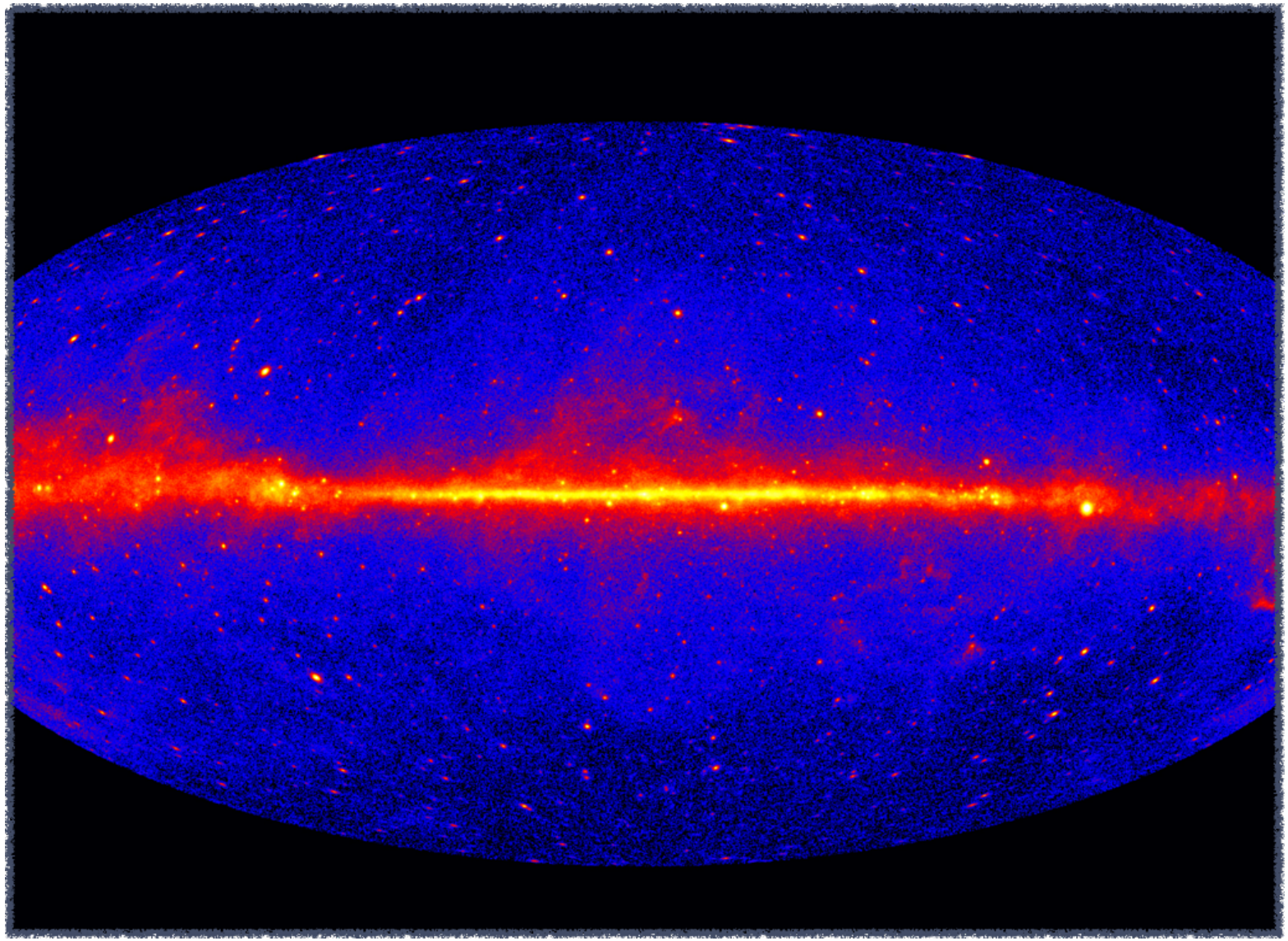
$$J_\gamma(E_\gamma) = 2\int_{E_\gamma} \frac{dE_\pi}{E_\pi} J_\pi(E_\pi) = \frac{2}{\gamma} J_\pi(E_\gamma) = \frac{\gamma}{2} 4\pi n_H \sigma_0 I_p(E_\gamma) \Lambda_\gamma$$

with $\Lambda_\gamma = \int_0^1 dx f(x) x^{\gamma-2}$ a numerical constant.



Diffuse galactic gamma-ray background

The diffuse galactic gamma ray background as recently observed by Fermi-LAT is likely produced by pp scattering.



Fermi-LAT

Gamma-ray emission in SNR

The local environment of a Super Nova Remnant (SNR) is a likely place for both interactions: proton-proton and ICS. Gamma ray observations are of paramount importance in tagging the actual production mechanism.

Hadronic models

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

γ rays emitted with the same spectrum of CR:

$$E^{-\gamma}$$

NOTE: this behavior of the gamma ray spectrum might be the smoking gun for CR acceleration. The flux of gamma rays should also exhibit the "pion bump" a peak in the flux due to pile up at the threshold $m_\pi/2$.

Leptonic models

$$e\gamma \rightarrow e\gamma$$

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

$$E^{-\frac{\gamma-1}{2}}$$

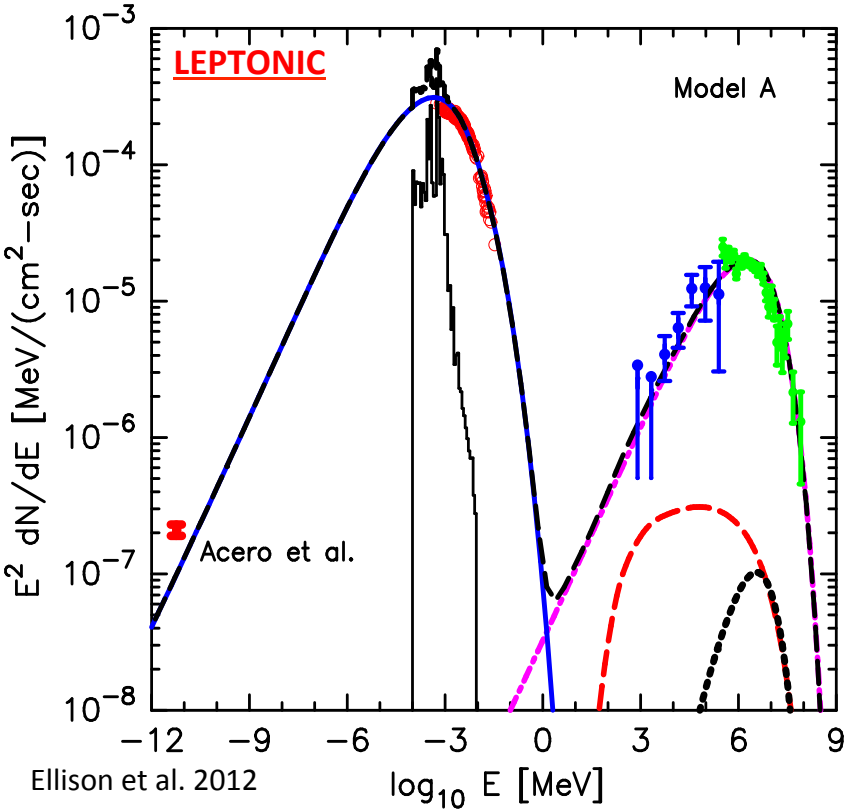
The case of RXJ1713

observed in keV, GeV and TeV range

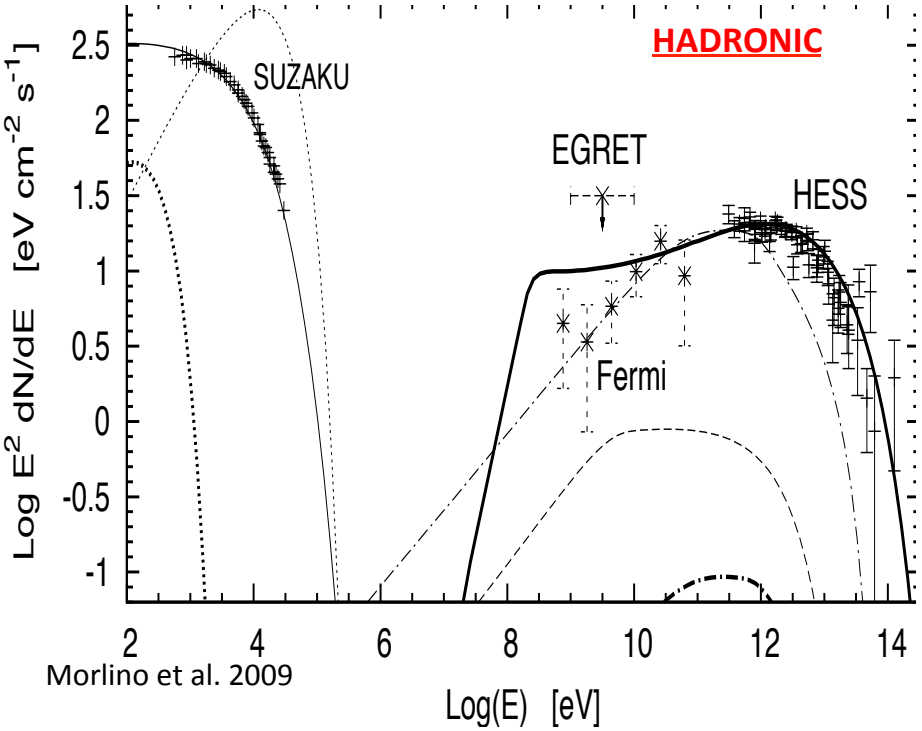
Bamba et al. (2009); Aharonian et al. (2004-2007); Abdo et al. (2011)

X-ray rims observed with B~160 μG are compatible with CR acceleration

hadronic origin of GeV-TeV emissions can be possible



Ellison et al. 2012



Morlino et al. 2009

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).

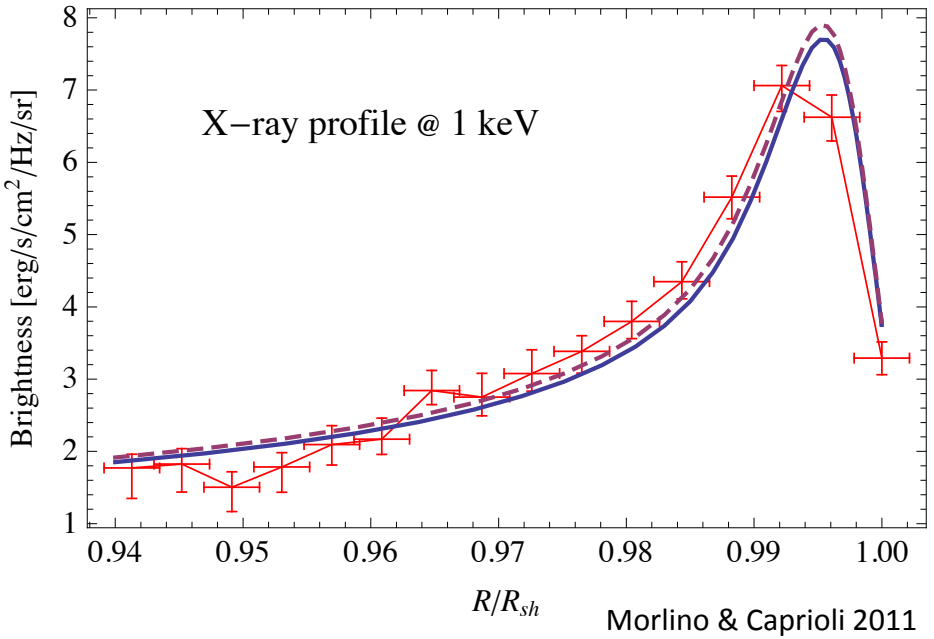
<u>complex environment, future high resolution gamma ray observations will distinguish different emitting regions</u>.

The case of Tycho

SNIa exploded in roughly homogeneous ISM (regular spherical shape)

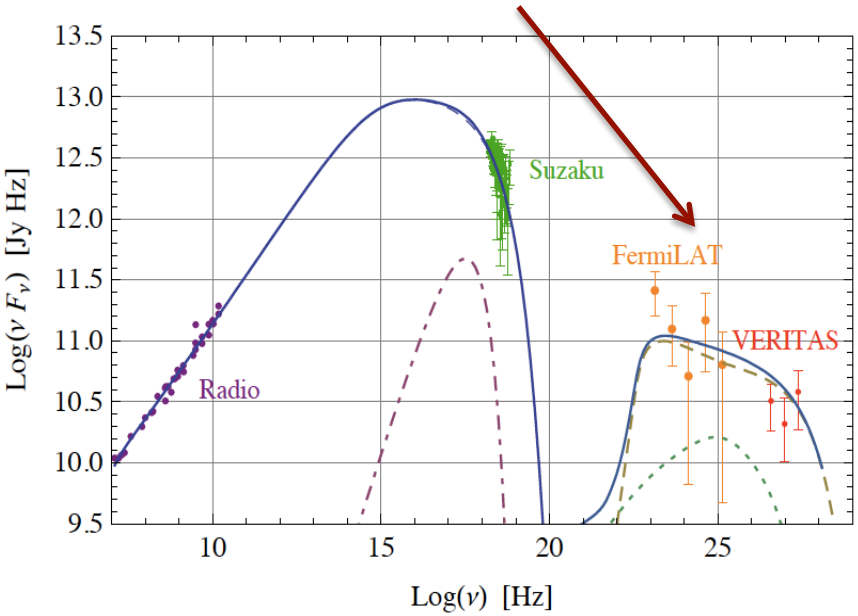
From X-ray observations B~300 μG

Maximum energy protons E_{max}~500 TeV



Morlino & Caprioli 2011

Steep spectrum hard to explain with leptons



Morlino & Caprioli 2011

Important example of the credibility level of theories based on DSA. Space resolved gamma ray observations would test different theoretical hypothesis.

Gamma-ray emission in SNR – quick summary

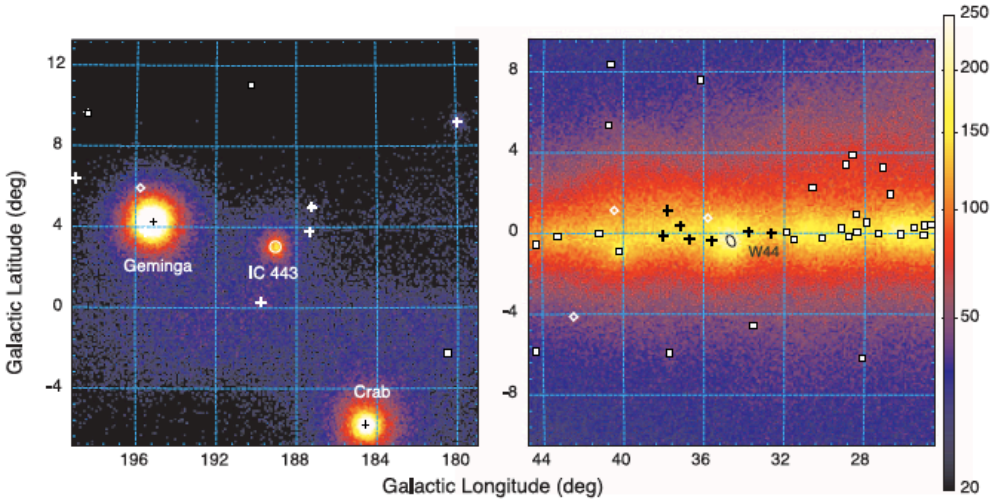
- The pion bump has not been seen so far (only in molecular clouds this feature seems observed, see later)

- 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.

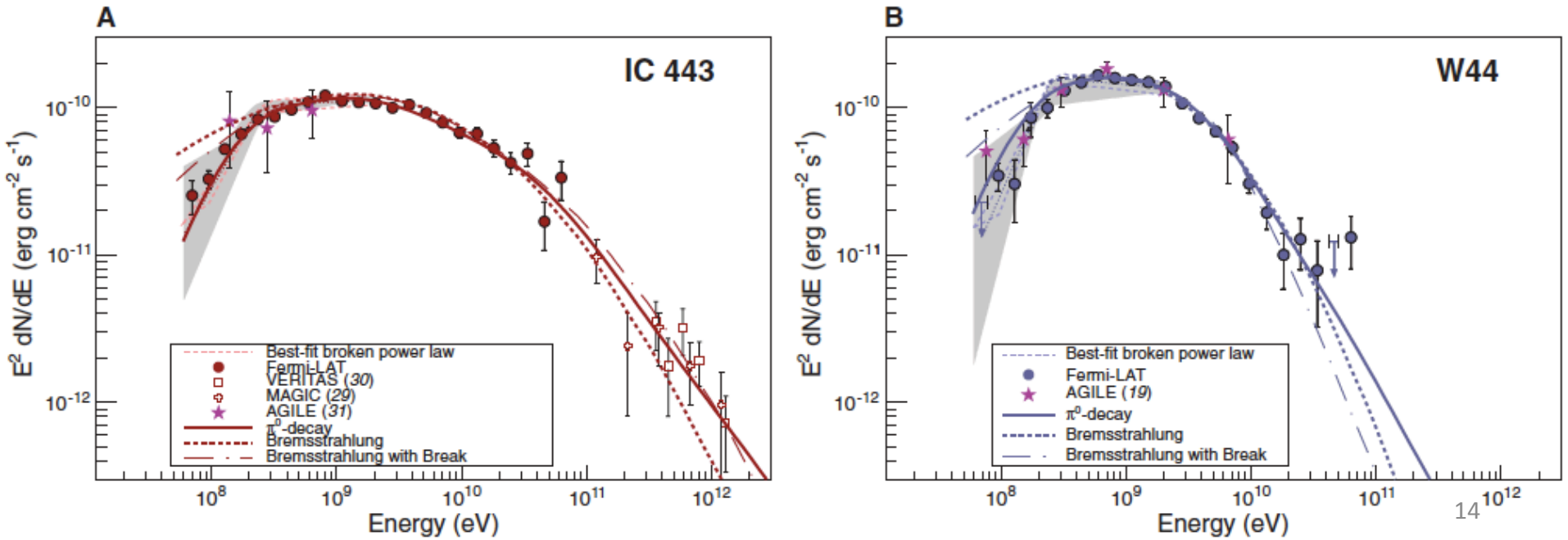
- Extension of the observations to high energies can provide an evidence of a cut-off in the PeV region (but low probability of finding a suitable SNR for this observations).

Gamma-ray emission from Molecular Clouds

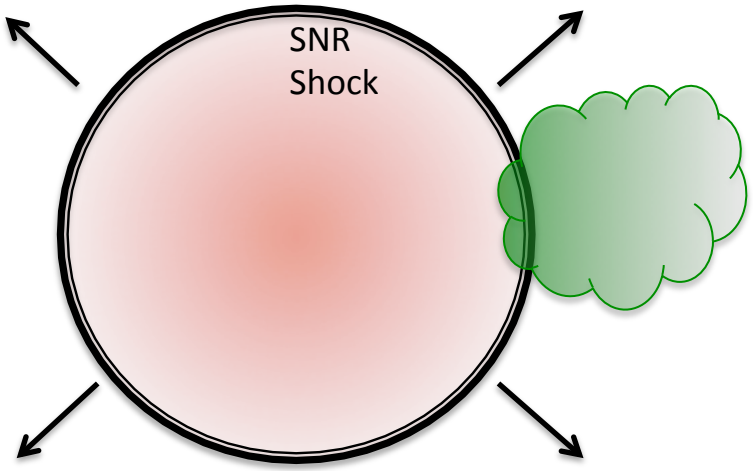
- Observation of the pion bump directly linked to pion decay, i.e. a pile up of photons at the energy threshold $m_\pi/2$.
- SN close to molecular clouds are very interesting laboratories to investigate CR propagation around sources and escape from sources.



Ackermann et al. 2013



Shock inside the cloud

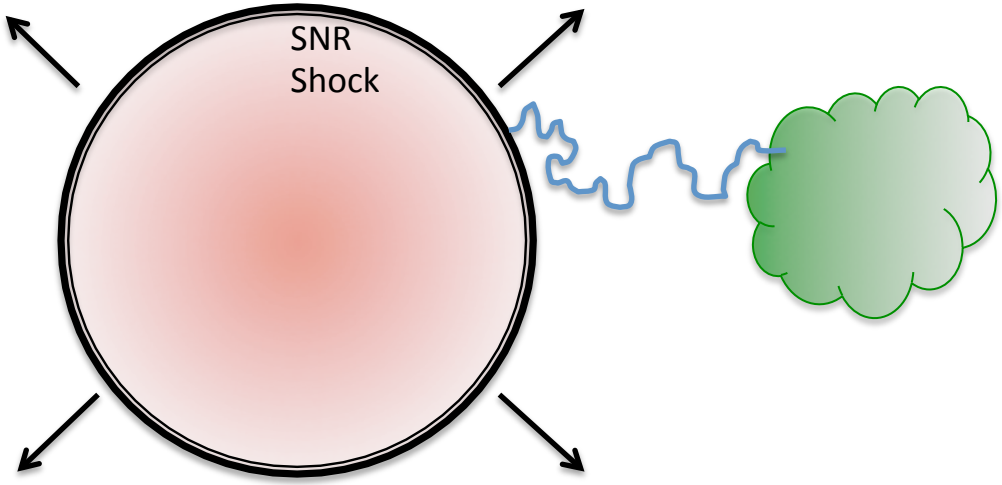


- the shock becomes collisional on scales

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

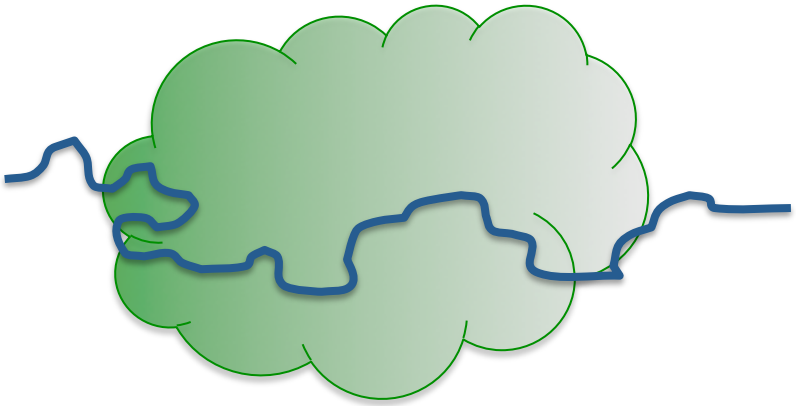
- It slows down since it feels the matter in the cloud, particle already accelerated escape streaming away and interacting with matter in the molecular cloud.

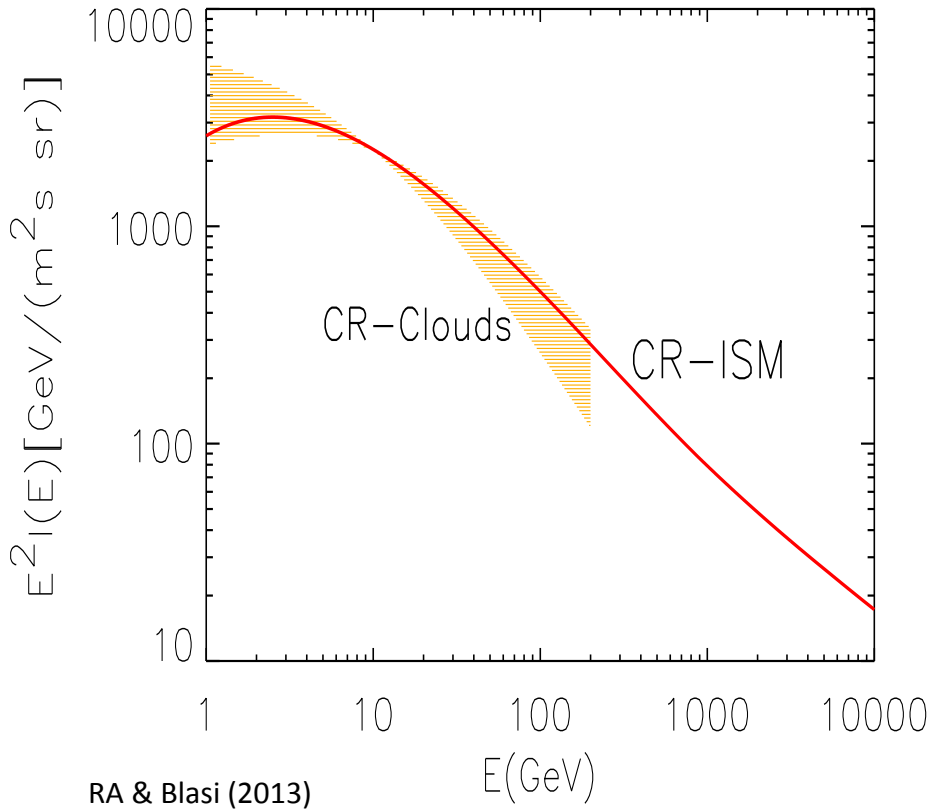
Shock outside the cloud



- 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, already detected 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.

Gamma-ray emission in MC – quick summary

- Escape is the link between acceleration and CR observed at the 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.

Charged pions decay and neutrinos

Proton-proton interaction gives rise also to the production of secondary charged pions that in turn decay producing (also through muon decays) neutrinos and electrons.

$$p + p \rightarrow \pi^{\pm} + \text{Anything}$$

$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu})$$

$$\mu^{\pm} \rightarrow e^{\pm} + \nu_{e}(\bar{\nu}_{e}) + \bar{\nu}_{\mu}(\nu_{\mu})$$

Pion decay

It is a two body decay (as for neutral pions decay) the spectrum of the final product is given by

$$\frac{dN}{dE_i} = \frac{m_\pi^2}{m_\pi^2 - m_\mu^2} \frac{1}{|\vec{p}_\pi|} = \frac{m_\pi^2}{m_\pi^2 - m_\mu^2} \frac{1}{\sqrt{E_\pi^2 - m_\pi}} \qquad \mathrm{i} = \mu, \nu$$

valid in the energy range (relativistic pions)

$$0 \leq E_\nu \leq E_\pi \left(\frac{m_\pi^2 - m_\mu^2}{m_\pi^2} \right) \qquad E_\pi \left(\frac{m_\mu}{m_\pi} \right)^2 \leq E_\mu \leq E_\pi$$

Muon decay

Muons produced in the decay of pions are fully polarized due to the parity non-conservation in weak interactions, using this fact it is possible to the determine the distribution of the emitted leptons in the muon decay, integrating over the emission angle of each emitted lepton (e, ν_μ,ν_e) it is possible to determine the spectrum of the emitted particles. Leaving the details of the calculations (see T.K. Gaisser book), in the relativistic limit one has

$$e, \nu_\mu \qquad \frac{dN}{dE_\nu} = \frac{2}{E_\mu}\left\{\frac{5}{6} - \frac{3}{2}\left(\frac{E_\nu}{E_\mu}\right)^2 + \frac{2}{3}\left(\frac{E_\nu}{E_\mu}\right)^3 - P_\mu\left[\frac{1}{6} - \frac{3}{2}\left(\frac{E_\nu}{E_\mu}\right)^2 + \frac{4}{3}\left(\frac{E_\nu}{E_\mu}\right)^3\right]\right\}$$

$$\nu_e \qquad \frac{dN}{dE_\nu} = \frac{1}{E_\mu}\left\{2 - 6\left(\frac{E_\nu}{E_\mu}\right)^2 + 4\left(\frac{E_\nu}{E_\mu}\right)^3 - 12P_\mu\left[-\frac{1}{6} + \frac{E_\nu}{E_\mu} - \frac{3}{2}\left(\frac{E_\nu}{E_\mu}\right)^2 + \frac{2}{3}\left(\frac{E_\nu}{E_\mu}\right)^3\right]\right\}$$

being P_μ the projection of muon polarization on the propagation direction, it is given by

$$P_\mu = \left[\frac{2E_\pi r}{E_\mu(1-r)} - \frac{1+r}{1-r}\right] \qquad r = \left(\frac{m_\mu}{m_\pi}\right)^2$$

With the kinematic limits $0 \le E_\nu \le E_\mu$

Neutrino fluxes

Let us consider the flux of neutrinos produced by the chain of reactions started by pp interactions. First we have to compute the flux of muon-neutrinos coming from the charged pions decay and the flux of muon and electron neutrinos coming from the muon decay. If ϕ_π is the flux of pions the flux of neutrinos will be:

$$\phi_\nu(E_\nu) = \int_{E_\pi^{min}} dE_\pi \frac{dN_{\mu\nu}}{dE_\nu}\phi_\pi(E_\pi) \qquad E_\pi^{min} = E_\nu \frac{m_\pi^2}{m_\pi^2 - m_\mu^2}$$

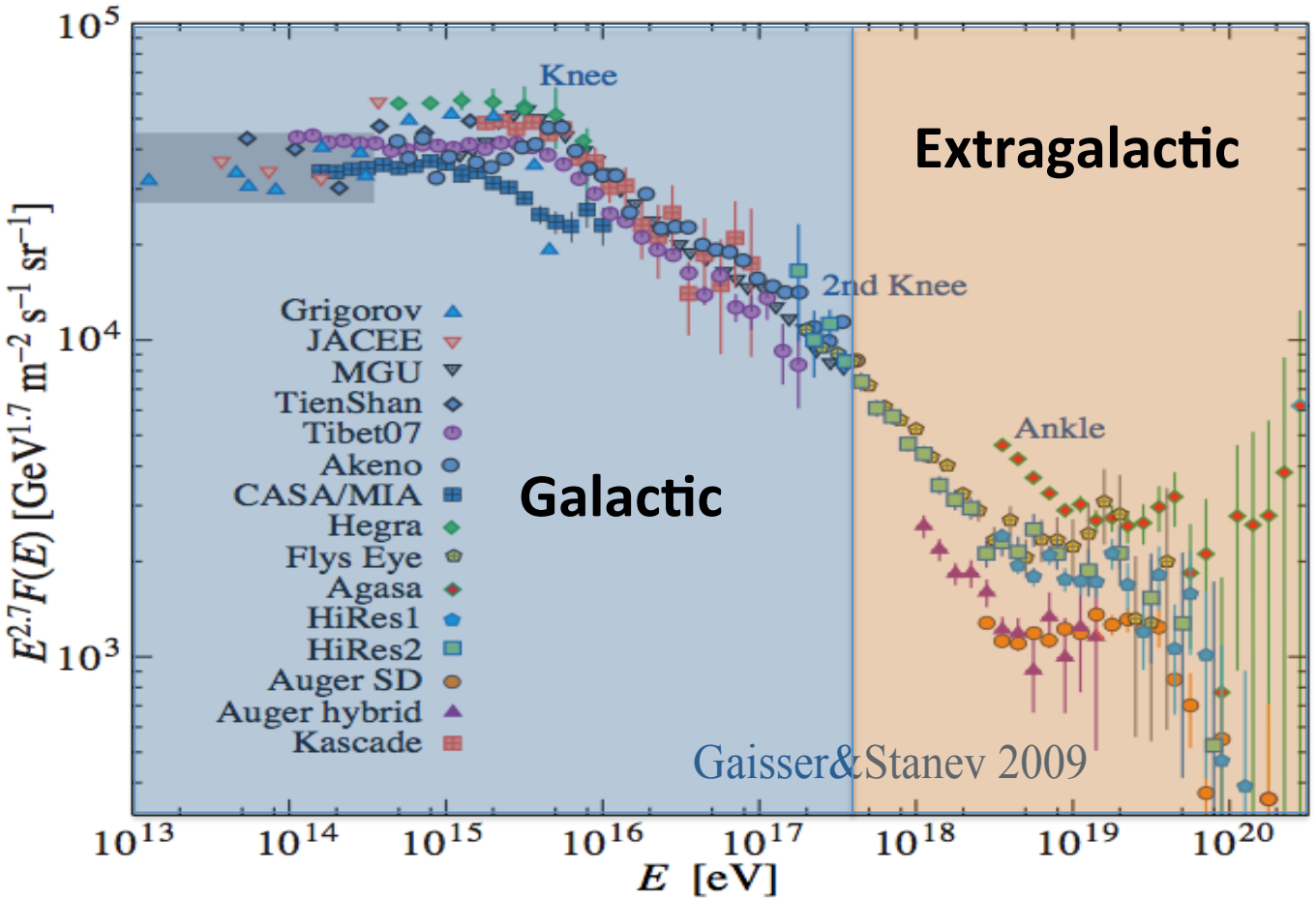
$$\phi_\nu(E_\nu) = \int_{E_\nu} dE_\mu \frac{dN_{e\nu\nu}}{dE_\nu} \int_{E_\mu}^{E_\mu/r} dE_\pi \frac{dN_{\mu\nu}}{dE_\mu}\phi_\pi(E_\pi) \qquad r = \left(\frac{m_\mu}{m_\pi}\right)^2$$

Using the appropriate spectrum for the final particles dN/dE_ν (as discussed before).

Generally speaking pions are produced by proton-proton interactions and the flux of pions has the same functional behavior of the primary protons flux. With some algebra it is possible to show that the same result holds for the flux of secondary neutrinos:

$$\phi_\nu(E_\nu) \propto \phi_p(E_\nu)$$

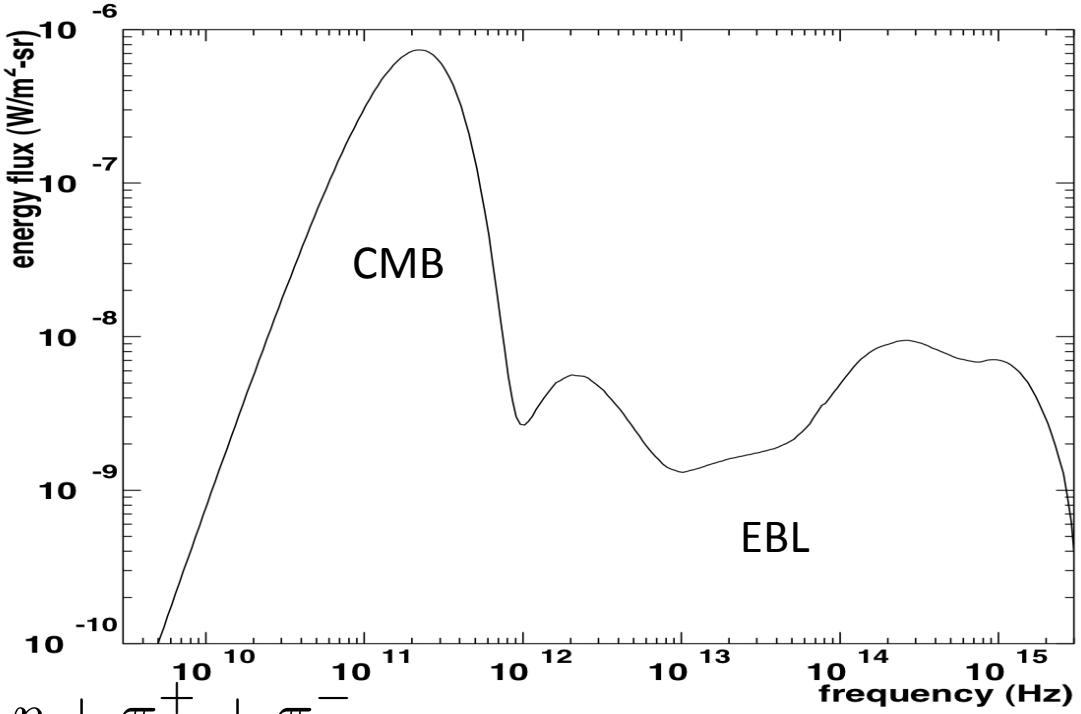
Extragalactic Cosmic Rays



At energies between 10^{17} eV and 10^{18} eV the observed CR are expected to be of extragalactic origin (their Larmor radius in the galactic magnetic field becomes larger than the size of the Galactic halo itself). The interaction suffered by extragalactic CR are dominated by astrophysical photons backgrounds: Cosmic Microwave Background (CMB) and Extragalactic Background Light (EBL).

Proton-Photon interactions

Let us consider now the interactions of high energy (relativistic) protons and astrophysical photon backgrounds. Relevant backgrounds are: the Cosmic Microwave Background (CMB) and the Extragalactic Background Light (EBL). Relevant processes are



Pair production

$$p + \gamma \rightarrow p + e^+ + e^-$$

Photo-pion production

$$p + \gamma \rightarrow p + \pi_0 \qquad p + \gamma \rightarrow p + \pi^+ + \pi^-$$

Both processes can be realized only if the proton has enough energy to produce the particles in the final state.

<u>Pair production</u>

$$E_{th} = \frac{(m_p + 2m_e)^2 - m_p^2}{2\epsilon(1 - cos\theta)} \simeq \frac{2m_e m_p}{\epsilon(1 - \cos\theta)}$$

CMB:
$\varepsilon = K_B T_0 \approx 2.3 \times 10^{-4}$ eV

$$E_{th} \simeq 2 \times 10^{18} eV \qquad (\theta = \pi)$$

EBL:
$\varepsilon \approx 1$ eV

$$E_{th} \simeq 5 \times 10^{14} eV \qquad (\theta = \pi)$$

Photo pion production

$$E_{th} = \frac{(m_p + m_\pi)^2 - m_p^2}{2\epsilon(1 - cos\theta)} \simeq \frac{m_p m_\pi}{\epsilon(1 - \cos\theta)}$$

CMB:
$E=K_B T_0 \approx 2.3 \times 10^{-4}$ eV

$$E_{th} \simeq 2 \times 10^{20} eV \qquad (\theta = \pi)$$

EBL: $\varepsilon \approx 1$ eV

$$E_{th} \simeq 1 \times 10^{17} eV \qquad (\theta = \pi)$$

These reactions become important at very high energy, the regime of the so-called Ultra High Energy Cosmic Rays (UHECR) observed with energies up to 10^{20} eV.

NOTE: the photo pion production process implies a huge Lorentz boost between the LAB frame and the rest frame of the proton, at the level of 10^{11} .

The energy losses of UHE protons due to pair-production and photo pion production, i.e. energy lost per unit time, can be computed in a very general form through

$$\frac{1}{E}\frac{dE}{dt} = \frac{c}{2\Gamma^2} \int_{\epsilon'_{min}} d\epsilon' f(\epsilon')\sigma(\epsilon') \int_{\epsilon'/2\Gamma} d\epsilon \frac{n_\gamma(\epsilon)}{\epsilon^2}$$

being ε' and ε'_{min} the photon energy and the threshold energy in the reference frame in which the proton is at rest, f(ε) is the so-called inelasticity of the process, i.e. the average fraction of energy lost by the proton in one interaction in the LAB reference frame, σ(ε) the cross-section of the process, $n_\gamma(\varepsilon)$ the number of background photons per unit volume and energy, $\Gamma = E/m_p$ the Lorentz factor of the incident proton.

Taking into account only the CMB, which has a predominant role at energy >10^{18} eV, we can analytically workout the behavior of energy losses. Using

$$n_{CMB}(\epsilon) = \frac{1}{\pi^2(\hbar c)^2} \frac{\epsilon^2}{\exp\left(\frac{\epsilon}{K_B T_0}\right) - 1}$$

one has

$$\frac{1}{E}\frac{dE}{dt} = \frac{cK_B T_0}{2\pi^2 \Gamma^2 (\hbar c)^2} \int_{\epsilon'_{min}} d\epsilon' f(\epsilon') \sigma(\epsilon') \epsilon' \left\{ -\ln\left[1 - \exp\left(-\frac{\epsilon'}{2\Gamma K_B T_0}\right)\right]\right\}$$

Pair production

At energies below threshold < 2x10^{18} eV, the pair production process is realized only through the CMB photons on the tail of the Planckian distribution. In this regime the inelasticity f and the cross section σ can be estimated at their threshold value:

$$f(\epsilon') \simeq \frac{2m_e}{m_p} \qquad \sigma_{ee}(\epsilon') \simeq \frac{\pi}{12}\alpha r_0^2 \left(\frac{\epsilon'}{m_e} - 2\right)^3 \qquad \epsilon'_{min} = 2m_e\left(1 + \frac{m_e}{m_p}\right)$$

$$\frac{1}{E}\frac{dE}{dt} = \frac{16c}{\pi}\frac{m_e}{m_p}\alpha r_0^2 \left(\frac{K_B T_0}{c\hbar}\right)^3 \left(\frac{\Gamma K_B T_0}{m_e}\right)^2 \exp\left(-\frac{m_e}{K_B T_0}\right)$$

Exponentially suppressed at $\Gamma K_B T_0 \ll m_e \quad E \ll 2 \times 10^{18} eV$

at energies higher than 2x10^{18} eV the pair production process becomes rapidly less efficient respect to photo pion production.

Photo pion production

Also in this case, at energies below threshold <2x10^{20} eV, being the interaction with the tail of the CMB distribution, we can determine f(ε) and σ(ε) at the threshold value

$$f(\epsilon') = \frac{\epsilon'}{m_p}\frac{1+m_\pi^2/m_p\epsilon'}{1+2\epsilon'/m_p} \quad \sigma(\epsilon') = \sigma_0\left(\frac{\epsilon'}{\epsilon'_{min}}-1\right) \quad \epsilon'_{min} = m_\pi\left(1+\frac{m_\pi}{m_p}\right)$$

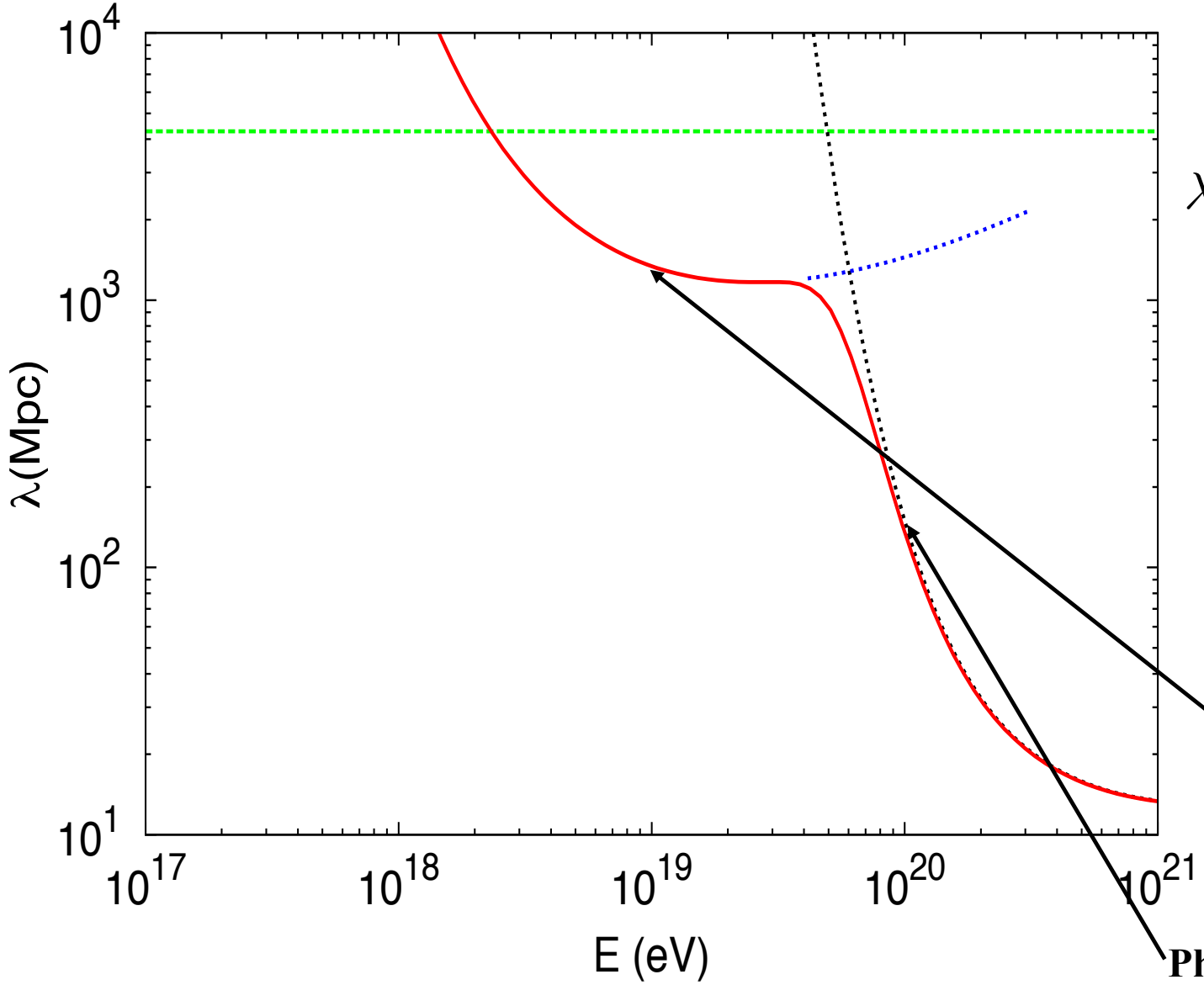
with σ_0 = 4x10^{-28} cm^2. The energy losses are

$$\frac{1}{E}\frac{dE}{dt} = \frac{2}{\pi^2}\left(\frac{K_B T_0}{c\hbar}\right)^3 \frac{\epsilon'_{min}}{m_p}\sigma_0 c \exp\left(-\frac{\epsilon'_{min}}{2\Gamma K_B T_0}\right)\left[1+4\frac{2\Gamma K_B T}{\epsilon'}\right]$$

At higher energies >2x10^{20} eV, the cross section becomes almost constant around 1x10^{-28} cm^2 and the average fraction of energy lost by the proton (in the LAB frame) f≈1/2 and

$$\frac{1}{E}\frac{dE}{dt} = c f_0 \sigma_0 n_{CMB} = 1.8\times 10^{-8} y^{-1}$$

Attenuation length of UHECR protons



$$\lambda = c\left(\frac{1}{E}\frac{dE}{dt}\right)^{-1}$$

Pair production

$p\,\gamma \rightarrow p\,e^+\,e^-$

Photopion production

$p\,\gamma \rightarrow N\,\pi$

Nucleus-Photon interactions

The interaction processes that involve high energy (>10^{17} eV) nuclei and astrophysical backgrounds (CMB and EBL) are: pair production and photo-disintegration.

$$(A,Z) + \gamma \rightarrow (A,Z) + e^+ + e^-$$

$$(A,Z) + \gamma \rightarrow (A-n, Z-n) + nN$$

Pair production $E_{th} = AE^p_{th} \simeq A \times 2 \times 10^{18}$ eV

This is the same processes that involves protons. The only relevant background involved is the CMB. The type of nucleus (A,Z) remains unchanged, only the particle's energy changes because of the interaction. The rate of energy losses can be computed starting from the rate of protons and using the scaling

$$f^A = \frac{f^p}{A} \qquad \sigma^A = Z^2 \sigma^p \qquad \left(\frac{1}{E}\frac{dE}{dt}\right)^{(A,Z)} = \frac{Z^2}{A}\left(\frac{1}{E}\frac{dE}{dt}\right)^{(p)}$$

Photo disintegration $E_{th} = AE^0_{th} \simeq A \times (3 \div 5) \times 10^{18}$ eV

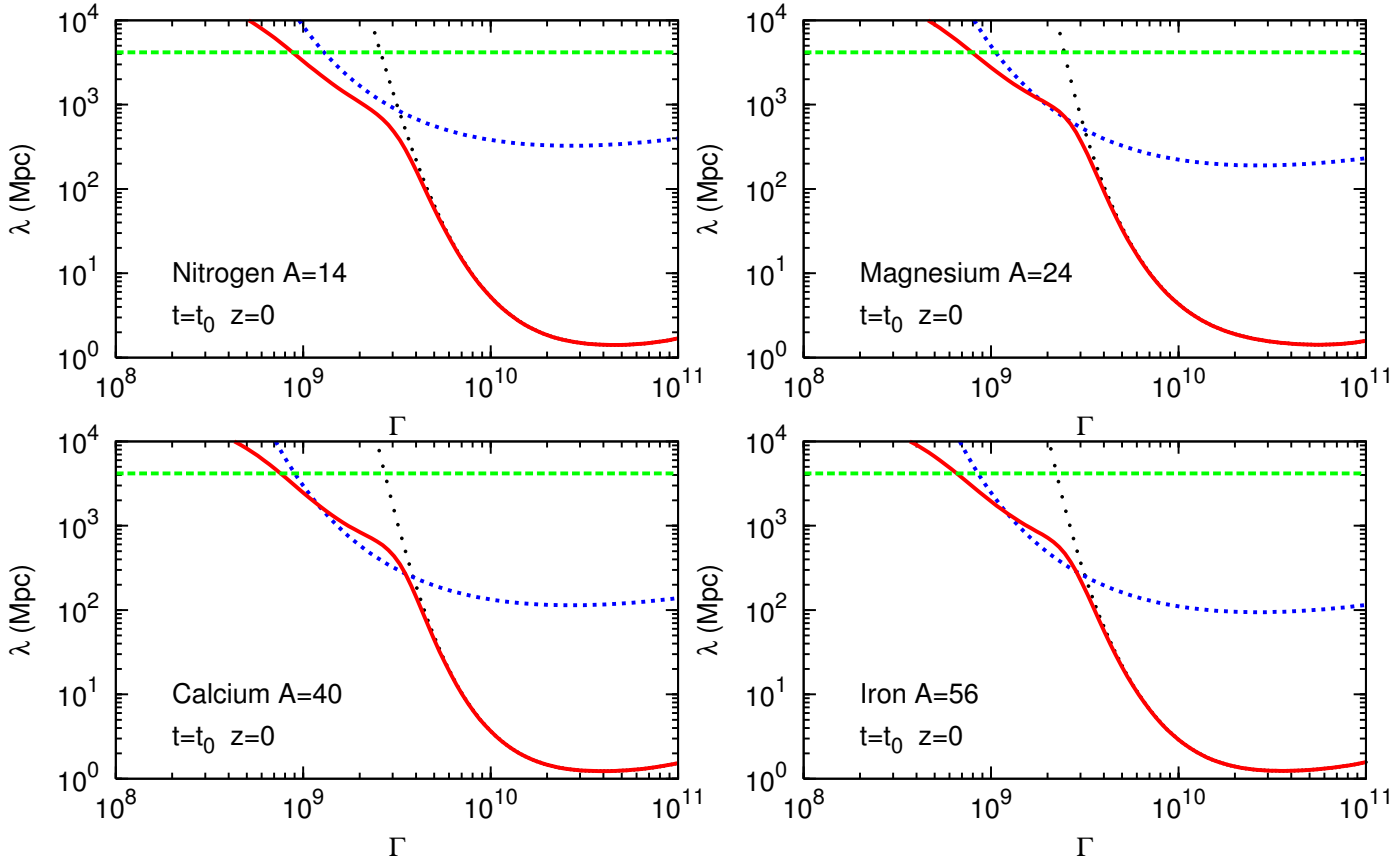
This process does not change the Lorentz factor of the nucleus, it changes only the type of nucleus that in the final state will be depleted by one or more nucleons. However, the dominant photo disintegration channel implies the emission of a single nucleon.
This process cannot be treated as a continuous decrease in energy of the propagating particle, because it implies a change in the particle type with the disappearance of the initial particle.

It can be treated as a “decaying” process with a typical “decaying time” given by

$$\frac{1}{\tau_A} = \frac{c}{2\Gamma^2} \int_{\epsilon'_{min}} d\epsilon' \sigma(\epsilon') \int_{\epsilon'/2\Gamma} d\epsilon \frac{n_\gamma(\epsilon)}{\epsilon^2}$$

NOTE: The propagation of UHE nuclei always implies the generation of secondary lighter UHE nuclei (the Lorentz factor is conserved!).

- **Pair production** blue dotted, only CMB is relevant.
- **Photo-disintegration** red solid, both CMB and EBL are relevant (black dotted CMB alone).



NOTE: The EBL has an effect only for photo-disintegration and only in the range $10^8 \leq \Gamma \leq 2 \times 10^9$

Just a little bit of Cosmology

We saw that UHE (>10^{17} eV) particles (both protons and nuclei) can travel over cosmological distance, hence Cosmology does matter!

The effect of the expansion of the universe is seen in the change in astrophysical backgrounds, in both density and radiation's energy, and in the UHE particle's energy.

CMB: it is the well known relic radiation of the big bang, with a Planckian distribution and the evolution with red shift through its temperature $T(z)=T_0(1+z)$.

EBL: composed of infrared, optical and ultraviolet photons produced by astrophysical sources and scattered by the ISM (dust) at present and past cosmological epochs. Has a less understood cosmological evolution, typically model dependent.

The rate of energy (adiabatically) lost by UHE particles (protons or nuclei) because of the expansion of the universe can be written as

$$\left(\frac{1}{\Gamma}\frac{d\Gamma}{dt}\right) = H(z) = H_0\sqrt{(1+z)^3\Omega_m + \Omega_\Lambda}$$

The rate of energy losses due to the processes discussed so far will get a red-shift dependence as follows:

$$n_\gamma(\epsilon) \to n_\gamma(\epsilon, z) \quad \epsilon \to \epsilon(1+z) \quad \Gamma \to \Gamma(1+z)$$

Transport in the extragalactic space - Protons

At energies E>10^{17} eV the effect of the galactic magnetic field is negligible and CR start to suffer the effects of the interactions with astrophysical backgrounds, namely the Cosmic Microwave Background (CMB) and the Extragalactic Background Light (EBL). Relevant interaction processes for protons are pair production and photo-pion production

$$p + \gamma \rightarrow p + e^+ + e^- \quad p + \gamma \rightarrow p + \pi^0 \quad p + \gamma \rightarrow p + \pi^+ + \pi^-$$

Assuming continuous energy losses

$$b(\Gamma, t) = \frac{d\Gamma}{dt} = \frac{c}{2\Gamma^2} \int_{\epsilon'_{min}}^{+\infty} \epsilon' \sigma(\epsilon') \int_{\epsilon'/2\Gamma}^{+\infty} \frac{n_\gamma(\epsilon)}{\epsilon^2} d\epsilon d\epsilon'$$

$$\frac{\partial n(\Gamma, t)}{\partial t} - \frac{\partial}{\partial \Gamma}\left[b(\Gamma, t) n(\Gamma, t)\right] = Q(\Gamma, t)$$

Model Parameters: γ injection power law index and $J_p = L_p\, n_s$ source emissivity

$$Q_{inj} = \frac{L_p(\gamma - 2)}{E_c^2}\left(\frac{E}{E_c}\right)^{-\gamma}$$

Uniform distribution of sources
the UHECR sources are continuously distributed with a density n_s.

$$J(E) = \frac{c}{4\pi} n_s \int_0^{z_{max}} dz \left|\frac{dt}{dz}\right| Q_{inj}(E_g(E, z)) \frac{dE_g}{dE}$$

Discrete sources
the UHECR sources are discretely distributed with a spacing d.

$$J(E) = \frac{1}{4\pi} \sum_i \frac{Q_{inj}(E_g(E, z_i))}{r_i^2 (1 + z_i)} \frac{dE_g(E, z_i)}{dE}$$

Transport in the extragalactic space - Nuclei

- ✓ Pair production: only the CMB is relevant, conservation of the nuclei specie A $\gamma \rightarrow$ A e^+ e^-.
- ✓ Photo-disintegration: CMB and EBL are relevant, conservation of the nuclei Lorentz factor (no nuclear recoil) A $\gamma \rightarrow$ (A-1) + N (most relevant process one nucleon emission)

Lorentz factor variation rate $b_A(\Gamma, z) = \Gamma \frac{Z^2}{A} \beta^p_{pair}(\Gamma, z) + \Gamma H_0 \sqrt{\Omega_m (1+z)^3 + \Omega_\Lambda}$

$$\frac{\partial n_A(\Gamma, t)}{\partial t} - \frac{\partial}{\partial \Gamma}[b_A(\Gamma, t) n_A(\Gamma, t)] + \frac{n_A(\Gamma, t)}{\tau_A(\Gamma, t)} = Q_A(\Gamma, t)$$

photo-disintegration "decay"

Injection: primary nuclei secondary nuclei

$$\frac{1}{\tau_A} = \frac{c}{2\Gamma^2} \int_{\epsilon'_{min}}^{+\infty} \epsilon' \sigma_A(\epsilon') \nu_A \int_{\epsilon'/2\Gamma}^{+\infty} \frac{n_\gamma(\epsilon)}{\epsilon^2} d\epsilon d\epsilon'$$

nuclei kinetic equation solution

$$n_A(\Gamma, z=0) = \int_0 dz \left| \frac{dt}{dz} \right| Q_A[\Gamma'(\Gamma, z)] \frac{d\Gamma'}{d\Gamma} e^{-\eta(\Gamma', z)}$$

$$\frac{d\Gamma'}{d\Gamma} = \frac{1+z'}{1+z} exp\left[\frac{Z^2}{A} \int_z^{z'} dz'' \frac{(1+z'')^2}{H(z'')} \left(\frac{db_0^p(\tilde{\Gamma})}{d\tilde{\Gamma}} \right)_{\tilde{\Gamma}=(1+z'')\Gamma''} \right]$$

Γ' solution of the energy losses equation

$$\frac{d\Gamma}{dt} = b_A(\Gamma, t)$$

photo-disintegration "life-time"

$$\eta(\Gamma', z) = \int_0^z dz' \left| \frac{dt}{dz'} \right| \frac{1}{\tau_A(\Gamma', z')}$$

Injection at the source

Assuming the injection of only one kind of nucleus A_0, with an homogenous distribution of sources.

$$Q_{A_0}(\Gamma, z) = \frac{(\gamma_g - 2)\mathcal{L}_0}{m_N A_0}\Gamma^{-\gamma_g}$$

$$\gamma_g = 2.3$$

Injection of secondary

dominant process: one nucleon emission Aγ→(A-1) N. Conservation of the Lorentz factor.

$$Q_A(\Gamma, z) = \frac{n_{A+1}(\Gamma, z)}{\tau_{A+1}(\Gamma, z)}$$

The flux of any secondary A can be determined solving the system (chain) of kinetic equations till the fixed A.

$$\begin{aligned}
\frac{\partial n_{A_0}(\Gamma,t)}{\partial t} - \frac{\partial}{\partial \Gamma}\left[n_{A_0}(\Gamma,t) b_{A_0}(\Gamma,t)\right] + \frac{n_{A_0}(\Gamma,t)}{\tau_{A_0}(\Gamma,t)} &= Q_{A_0}(\Gamma,t) \\
\frac{\partial n_{A_0-1}(\Gamma,t)}{\partial t} - \frac{\partial}{\partial \Gamma}\left[n_{A_0-1}(\Gamma,t) b_{A_0-1}(\Gamma,t)\right] + \frac{n_{A_0-1}(\Gamma,t)}{\tau_{A_0-1}(\Gamma,t)} &= \frac{n_{A_0}(\Gamma,t)}{\tau_{A_0}(\Gamma,t)} \\
&\vdots \\
\frac{\partial n_{A}(\Gamma,t)}{\partial t} - \frac{\partial}{\partial \Gamma}\left[n_{A}(\Gamma,t) b_{A}(\Gamma,t)\right] + \frac{n_{A}(\Gamma,t)}{\tau_{A}(\Gamma,t)} &= \frac{n_{A+1}(\Gamma,t)}{\tau_{A+1}(\Gamma,t)}
\end{aligned}$$

Secondary nucleons

$$\frac{\partial n_p(\Gamma,t)}{\partial t} - \frac{\partial}{\partial \Gamma}\left[b_p(\Gamma,t) n_p(\Gamma,t)\right] = Q_p^A(\Gamma,t)$$

each secondary nucleus in the decay chain of A_0 produces almost one nucleon A γ → (A-1) N

$$Q_p^A(\Gamma,z) = Q_A(\Gamma,z) = \frac{n_{A+1}(\Gamma,z)}{\tau_{A+1}(\Gamma,z)}$$

Only CMB is relevant
pair and photo-pion production

$$b_p(\Gamma,z) = \Gamma[\beta_{pair}^p(\Gamma,z) + \beta_{pion}^p(\Gamma,z)] + \Gamma H_0 \sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}$$

nucleons kinetic equation solution

$$n_p^A(\Gamma, z=0) = \int_0 dz \left|\frac{dt}{dz}\right| Q_p^A\left[\Gamma'(\Gamma,z)\right] \frac{d\Gamma'}{d\Gamma} \qquad n_p(\Gamma, z=0) = \sum_{A<A_0} n_p^A(\Gamma, z=0)$$

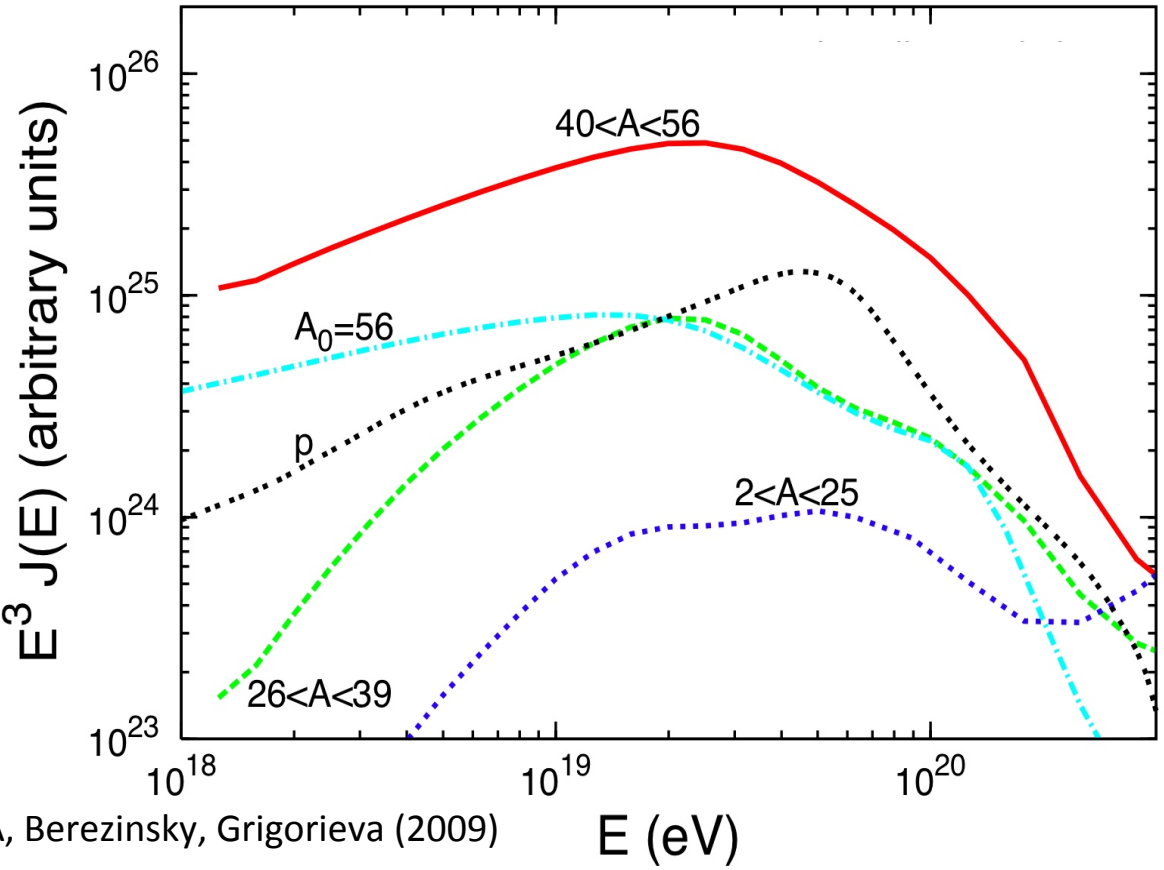
Γ' solution of the energy losses equation

$$\frac{d\Gamma}{dt} = b_p(\Gamma,t)$$

$$\frac{d\Gamma'}{d\Gamma} = \frac{1+z'}{1+z} \exp\left[\int_z^{z'} dz'' \frac{(1+z'')^2}{H(z'')} \left.\frac{db_p(\tilde{\Gamma})}{d\tilde{\Gamma}}\right|_{\tilde{\Gamma}=(1+z'')\Gamma}\right]$$

Caveat - no single specie composition

It is <u>impossible</u> to observe on earth a pure heavy nuclei spectrum, even if sources inject only heavy nuclei of a fixed specie on earth we will observe all secondary (protons too) produced by photo-disintegration.



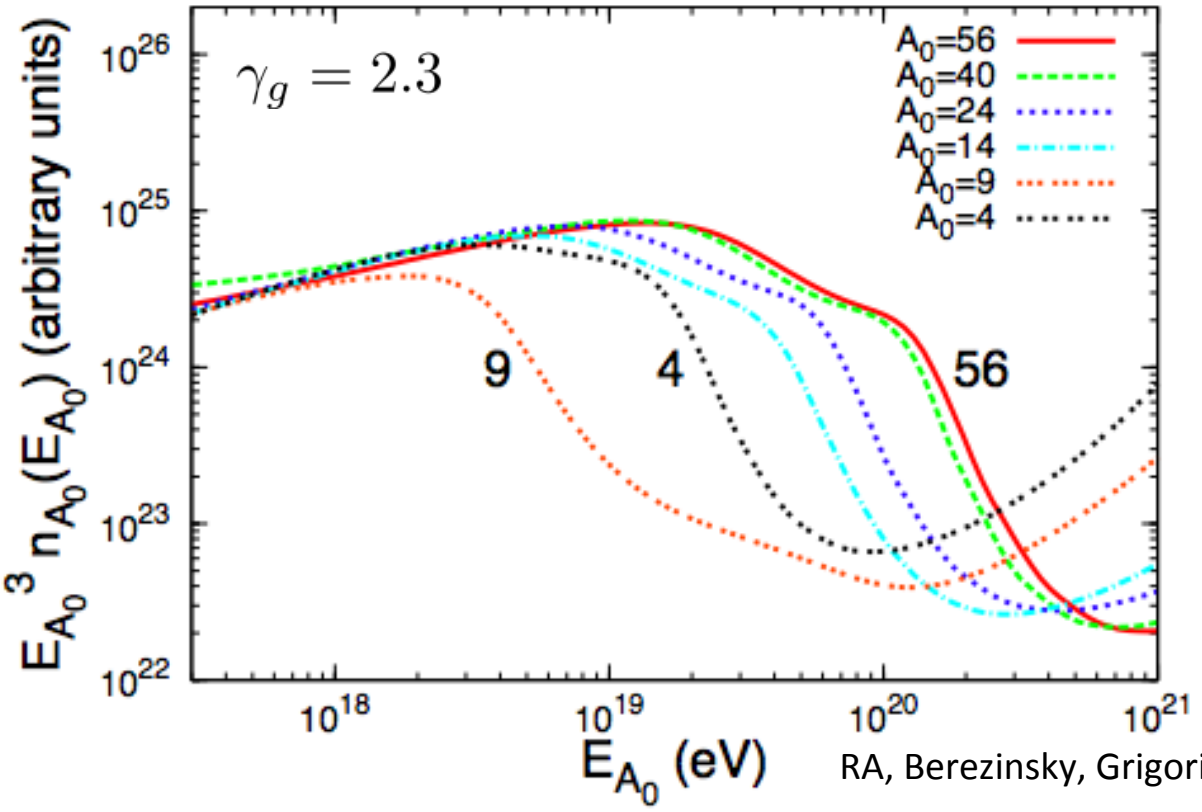
RA, Berezinsky, Grigorieva (2009)

Nuclei high energy behavior

Critical Lorentz factor $\Gamma_c(A,\Gamma,t)$

$$\beta^A_{e^+e^-}(\Gamma,t) + H_0(t) = \beta^\Gamma_{dis}(A,t)$$

The critical Lorentz factor fixes the scale at which photo-disintegration becomes relevant, for heavy nuclei it is almost independent of the nuclei specie



$$E_{cut}(A) = A m_N \Gamma_c$$

$$\Gamma_c \simeq 2 \times 10^9$$

note that the cut-off energy is proportional to the atomic mass-number A of nuclei

RA, Berezinsky, Grigorieva (2009)

Interaction vs maximum energy

The highest energy behavior of the fluxes is dominated by particles interaction with backgrounds (nuclei photo-disintegration or protons photo-pion) depending on the maximum acceleration energy at the sources.

✓ **Protons**

$$E^{p}_{max} > E_{GZK} \simeq 10^{20} eV$$

✓ **Nuclei**

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

$$E_{max}(A) > E_{cut}(A)$$

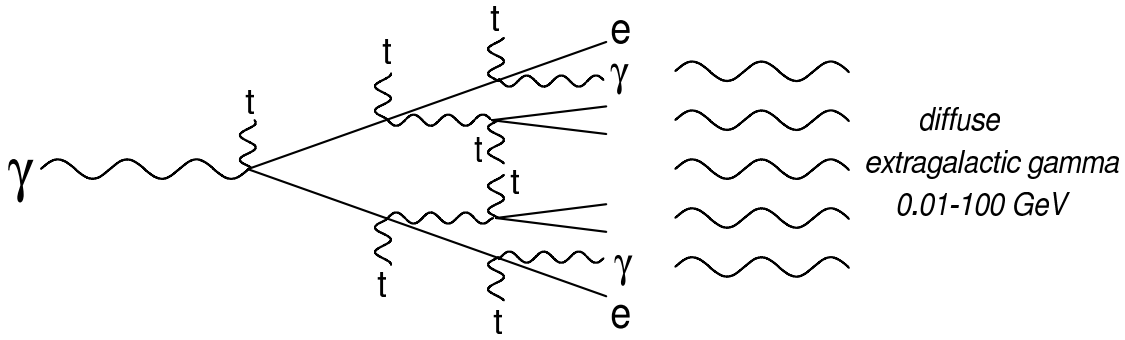
$$E^{p}_{max} > \frac{A}{Z} m_N \Gamma_c \simeq 4 \times 10^{18} eV$$

Only under these conditions the high energy flux is shaped by the protons photo-pion production process (GZK) or by the nuclei photo-disintegration process.

Secondary emission gamma rays

Proton and nuclei interactions with astrophysical backgrounds produce hadronic particles, mainly pion, that in turn decay giving rise to the production of secondary UHE photons, electron positron pairs (and neutrinos, see later).

$$p(A)\gamma \rightarrow e^{\pm}$$
$$p(A)\gamma \rightarrow \pi^0 \rightarrow \gamma\gamma$$



Cascade develops on CMB and EBL through pair production and ICS, the typical threshold energy scales for pair production are

$$\mathcal{E}_{CMB} \simeq 2.5 \times 10^{14} eV \qquad \mathcal{E}_{EBL} \simeq 2.5 \times 10^{11} eV$$

The radiation left behind by the cascade is restricted to energies below the lowest threshold.

$$n_\gamma(E_\gamma) \propto \begin{cases} E_\gamma^{-3/2} & E_\gamma < \mathcal{E}_X \\ E_\gamma^{-2} & \mathcal{E}_X \leq E_\gamma \leq \mathcal{E}_{EBL} \end{cases}$$

The cascade development has a universal behavior independent of the energy and spectrum of the initial photon/pair

$$\mathcal{E}_X = \frac{\mathcal{E}_{EBL}}{3}\frac{\epsilon_{CMB}}{\epsilon_{EBL}} \simeq 10^7 \text{ eV}$$

ε_{CMB} = 3x10^{-4} eV and ε_{EBL} = 1 eV are the typical energies of the background photons.

The normalization of the cascade spectrum can be easily determined imposing energy conservation, i.e. the total energy of photons\pairs that started the cascades should be equal to the total energy of the cascading particles.

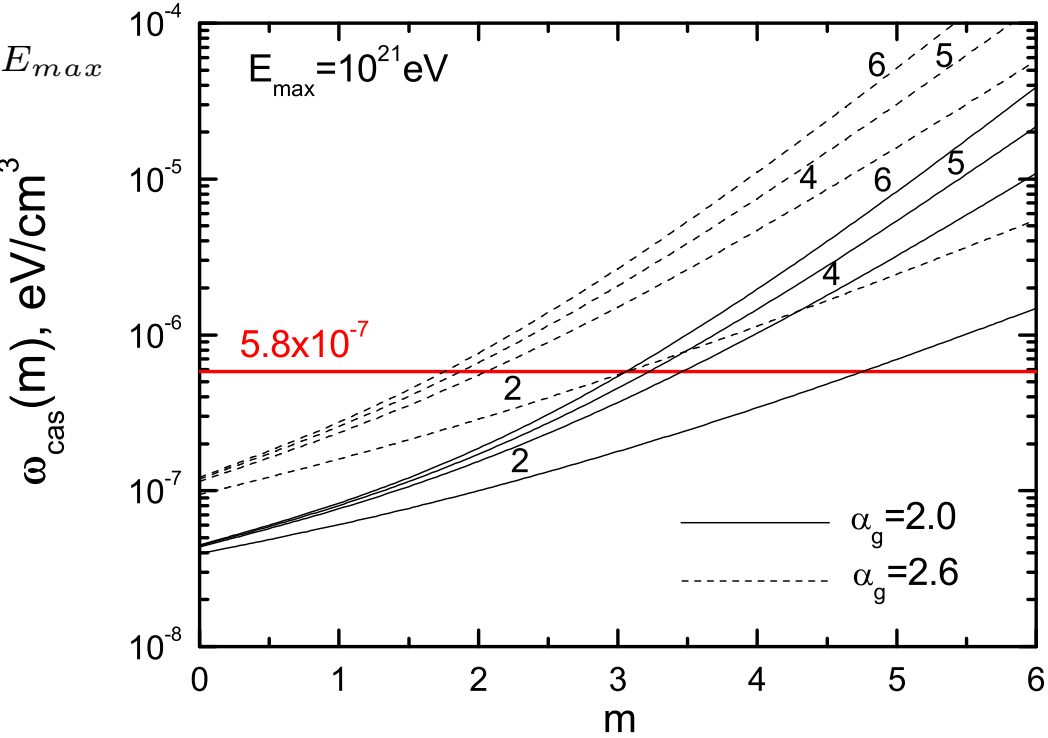
$$\omega_{cas}^{max} = \int dE_\gamma E_\gamma n_\gamma(E_\gamma)$$

Fermi-LAT data (ω_{cas}= 5.8x10^{-7} eV/cm^3) can be compared with the theoretical expectation above to constrain models of UHECR.

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

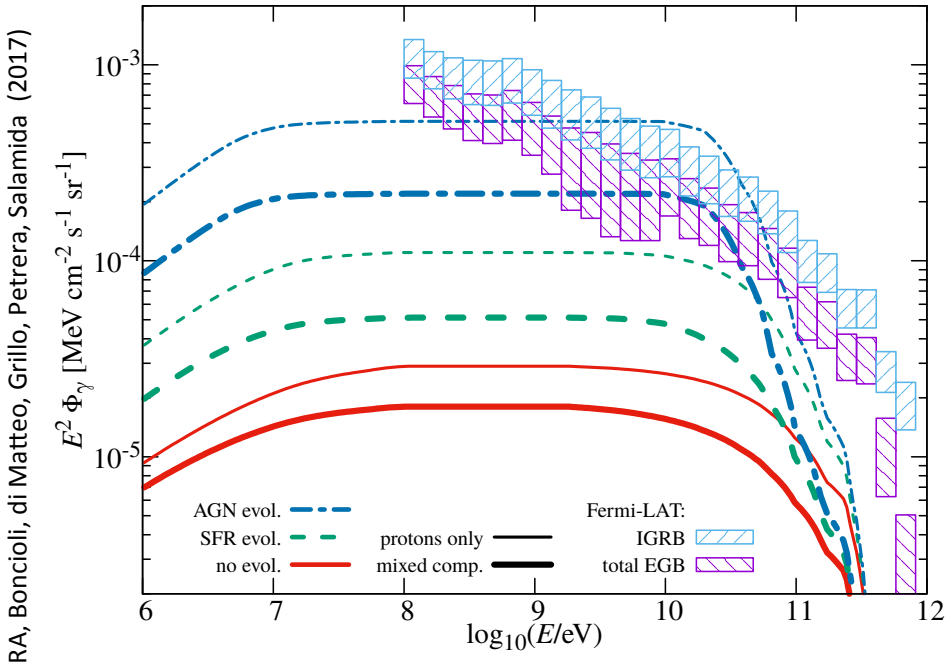
This comparison already fixes stringent limits on the cosmological evolution of sources of UHE protons.

NOTE: the production of secondary gamma rays and neutrinos is maximal in the case of a pure proton composition of UHECR.

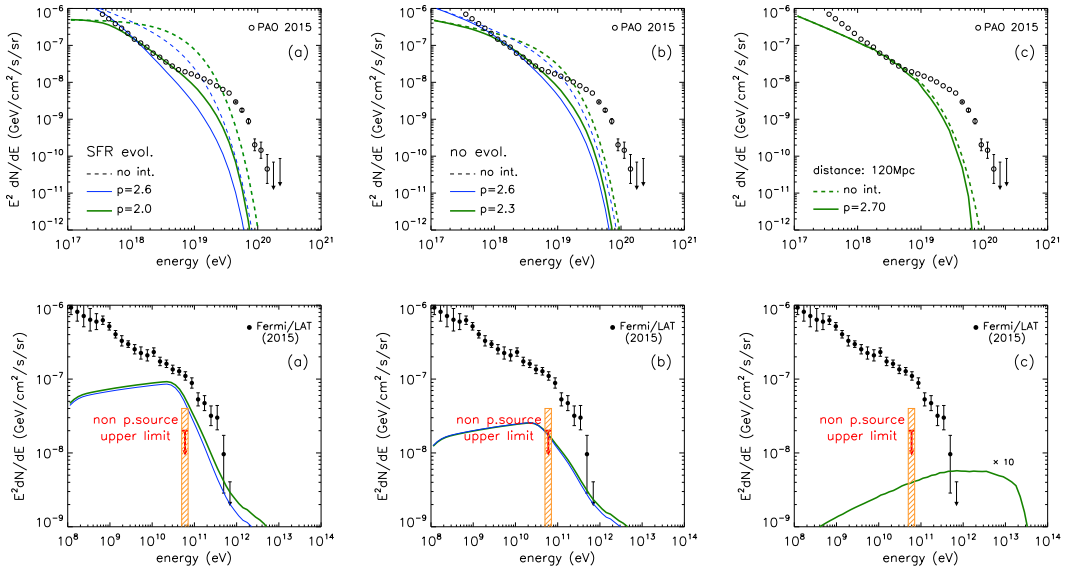


Berezinsky, Gazizov, Kachelriess, Ostapchenko (2011)

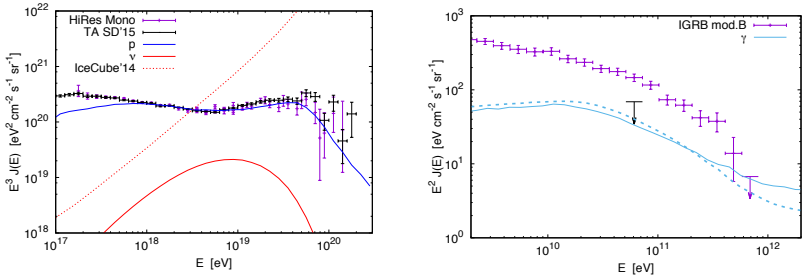
Diffuse gamma rays



- ✓ Diffuse extragalactic gamma-ray 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.



Liu, Taylor, Wang, Aharonian (2016)



Berezinsky, Gazizov, Kalashev (2016)

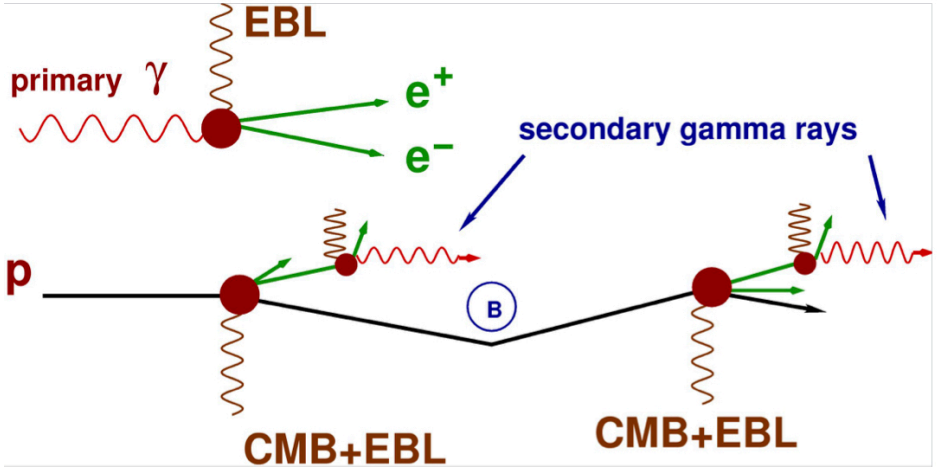
γ-rays from distant AGN

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.

NOTE: at large distances the contribution of secondary gammas dominates.

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

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



NOTE: this model requires low IMF at the level of femtogaus (10^{-15} G).

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

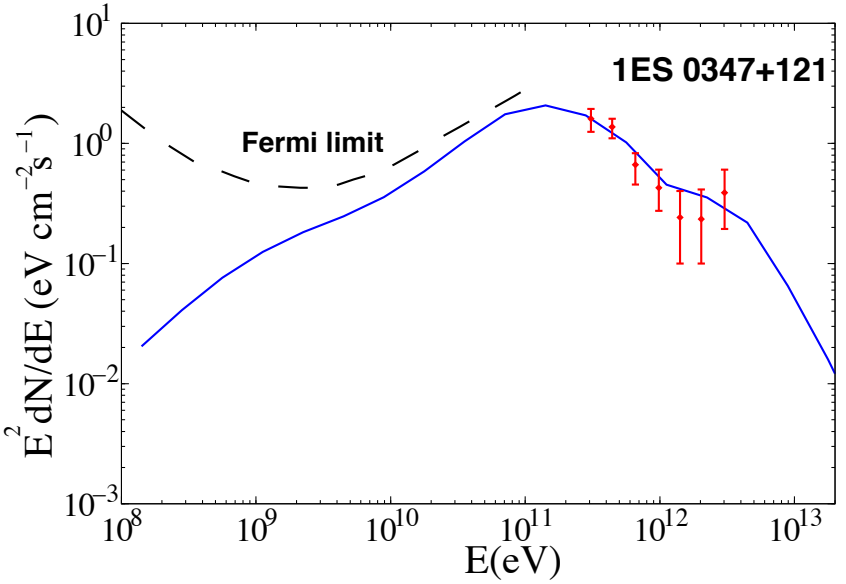
The spectrum of the final cascade is universal. The EM cascade behaves as a sort of calorimeter that redistribute the initial energy into gamma rays and neutrinos with a given spectrum, as discussed above.

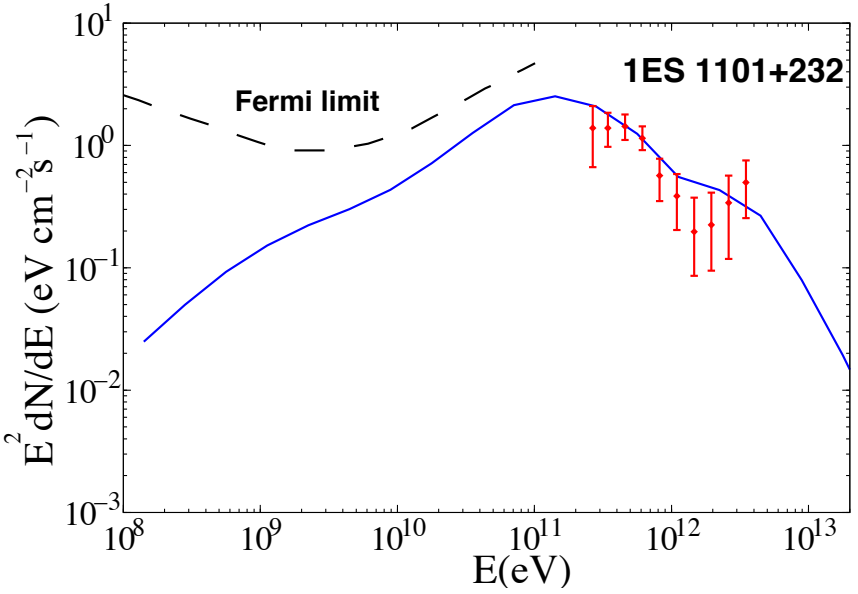
Ferrigno, Blasi, De Marco (2004)

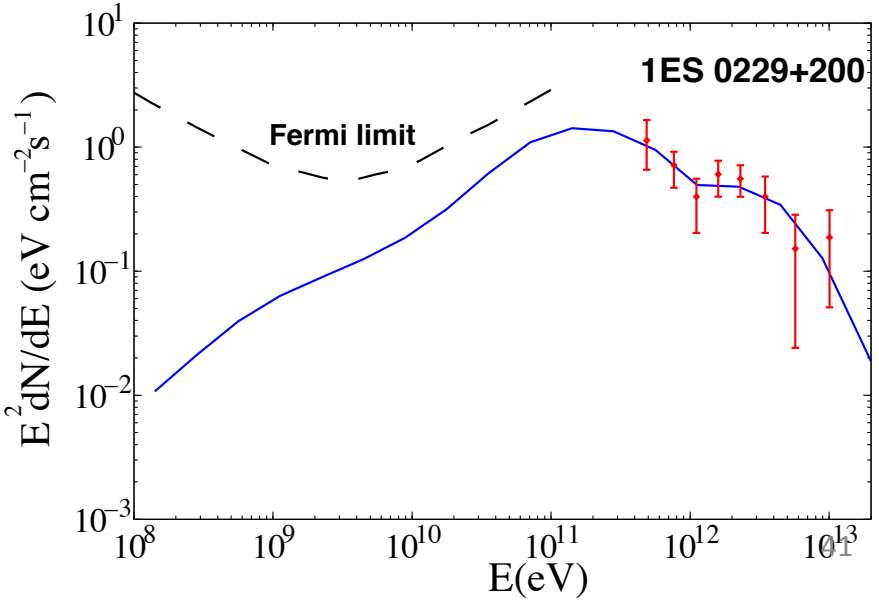
Essey, Kalashev, Kusenko, Beacom (2009-13)

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 secondary. If E_{max} is large (>10^{19} eV) interaction on CMB dominates, otherwise photo-pion production on EBL plays a role (provided that E_{max}>10^{8} GeV).

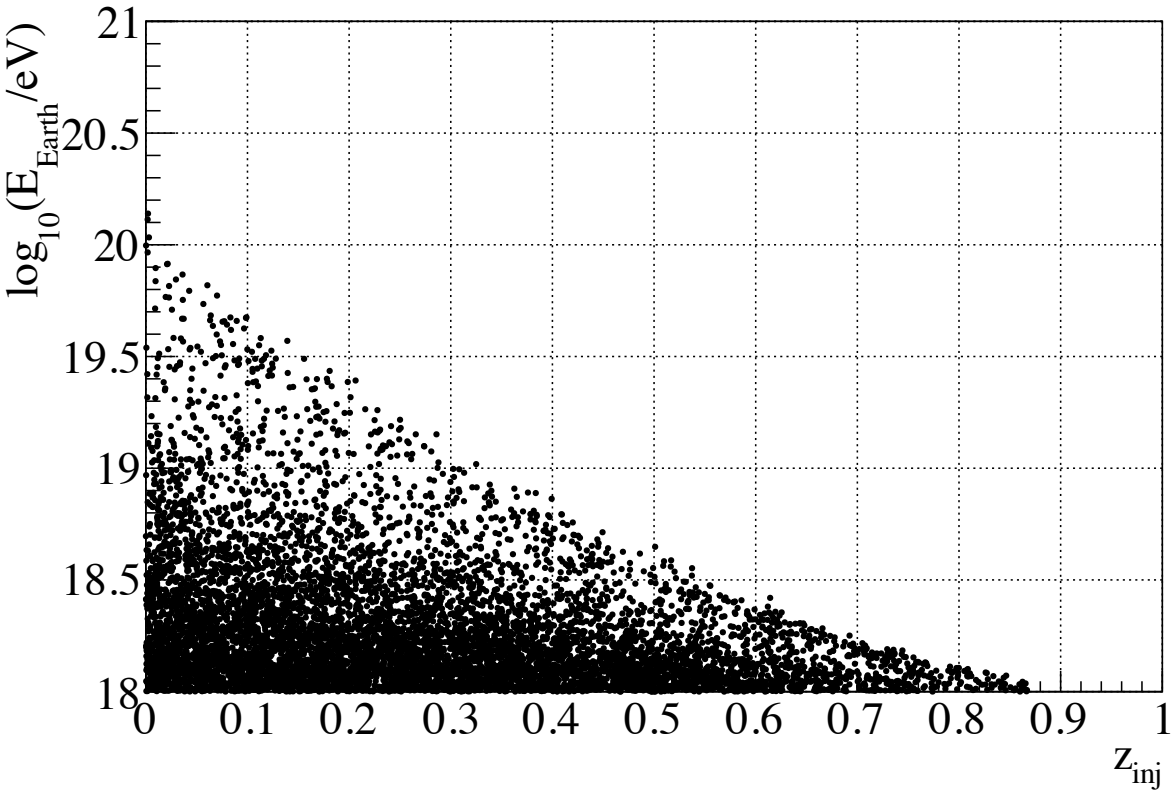






Essey, Kalashev, Kusenko, Beacom (2011)

Looking farther away – secondary neutrinos



- The universe accessible in UHECRs (protons or nuclei) is not larger than redshift z~1.

$$p(A)\gamma \rightarrow \pi^{\pm} \rightarrow e^{\pm}, \nu$$

- Only the observation of secondary cosmogenic neutrinos can open up the far away universe (until the first stars redshift z~10) in the UHE window.

- Photo-hadronic interactions are less efficient in the case of nucleons bounded inside nuclei. The production of secondary cosmogenic neutrinos and gamma rays strongly tied to UHECR mass composition.

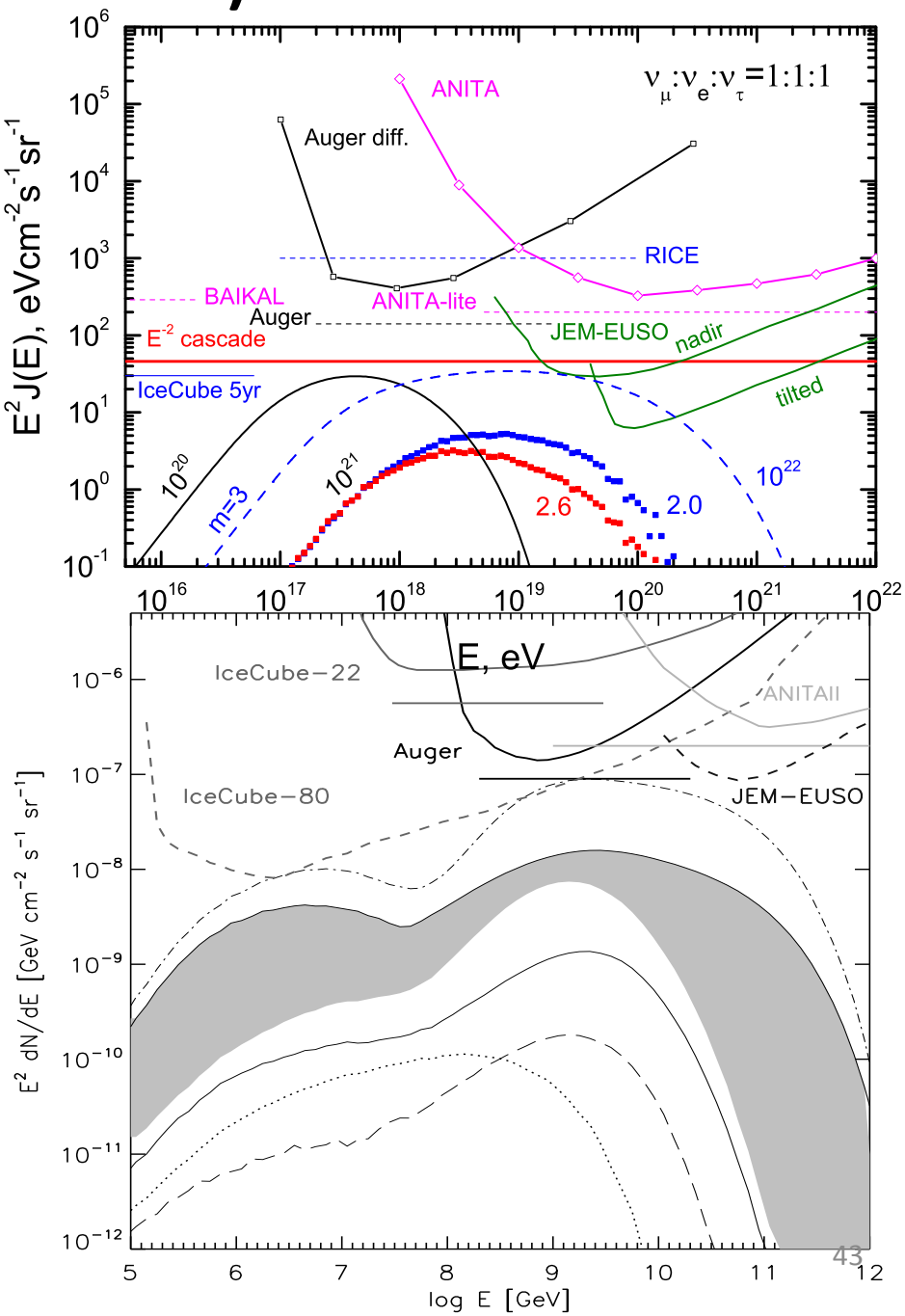
ν spectra – Pure protons (dip model)

✓ **Photo-pion production**

On EBL has a threshold of about 10^8 GeV, broadened by the energy distribution of EBL photons. The pion production by UHE protons on the EBL can account for the production of PeV neutrinos.

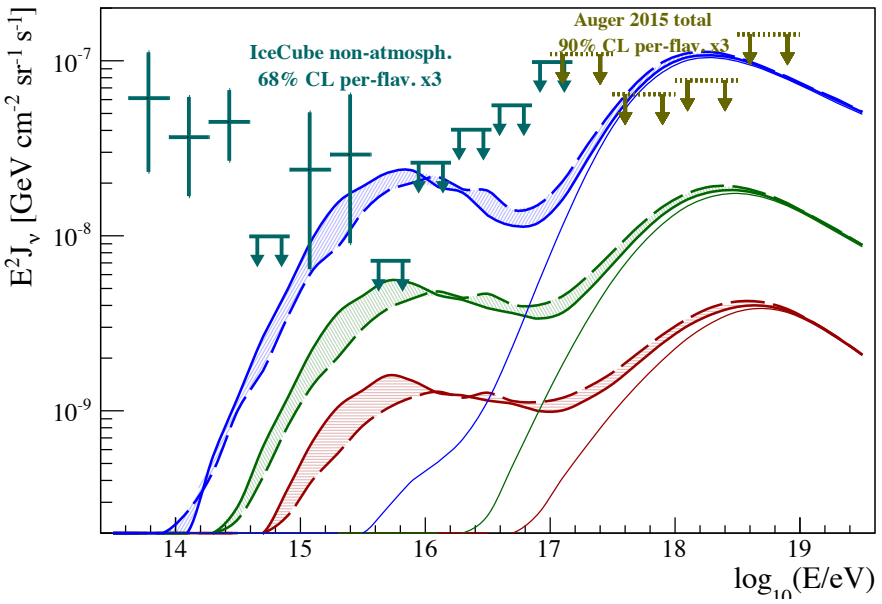
✓ **Cosmological evolution**

The result on the diffuse flux depends on the cosmological evolution assumed for the sources. The IceCube observations at PeV can be marginally reproduced only in the case of strong cosmological evolution (AGN like).



Berezinsky, Gazizov, Kachelriess, Ostapchenko (2010)

Kotera, Allard, Olinto (2011)



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

✓ EeV neutrinos in the dip model

Fermi-LAT observations constrain cosmogenic neutrino fluxes. Detectability only for high maximum energies (>10^{20} eV) and strong cosmological evolution of the sources (m>2)

✓ PeV neutrinos in the dip model

PeV neutrinos can be produced by protons photopion interactions on the EBL. Fluxes (≈ 10^{-9} GeV/cm^s s sr) below the Ice Cube detection capabilities.

✓ PeV neutrinos from popIII stars

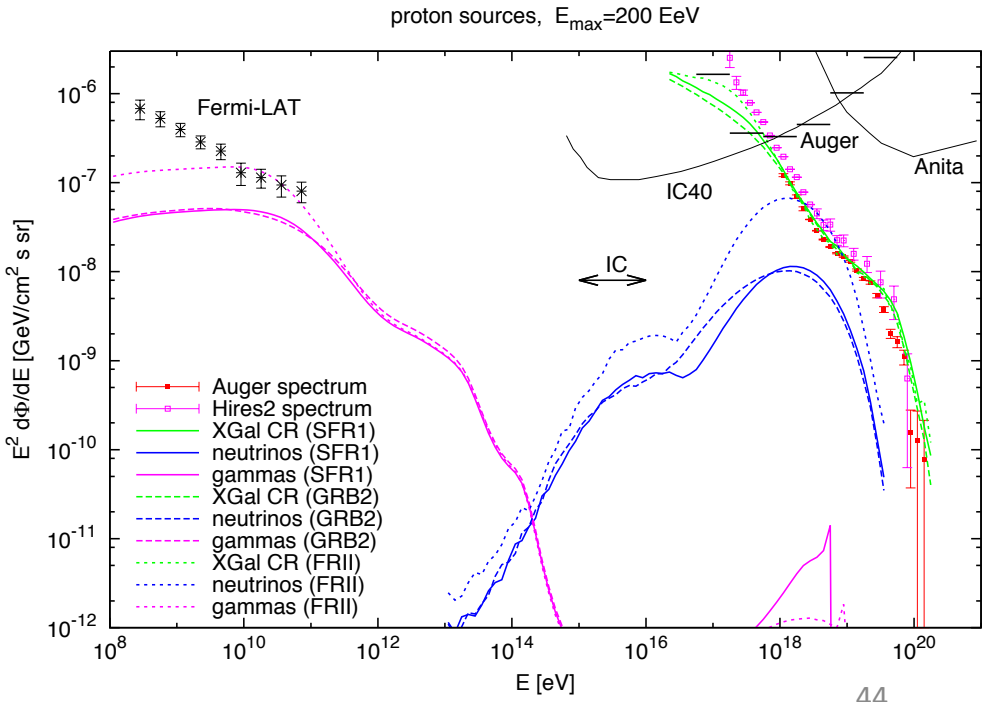
- massive stars (100 M_{sol}) at z ≈ 10 ÷ 15
- protons acceleration with γ_g =2.0 ÷ 2.3
- $E_{max} = 10^{21}$ eV

$$E_\nu = \frac{1}{20}\frac{E_{p\gamma\to\pi}}{(1+z_b)^2} \simeq 7.5\times10^{15}\left(\frac{20}{1+z_b}\right)^2 \; eV$$

$$E_\nu^2 J_\nu(E_\nu) = 0.1\frac{c}{4\pi}\frac{\omega_p(z_b)}{(1+z_b)^4}\frac{1}{\ln(E_{max}/E_{min})}$$

$$\omega_p \gtrsim 10^{-6}\mathrm{eV/cm}^3 \quad \underline{\text{Ice Cube detectable}}$$

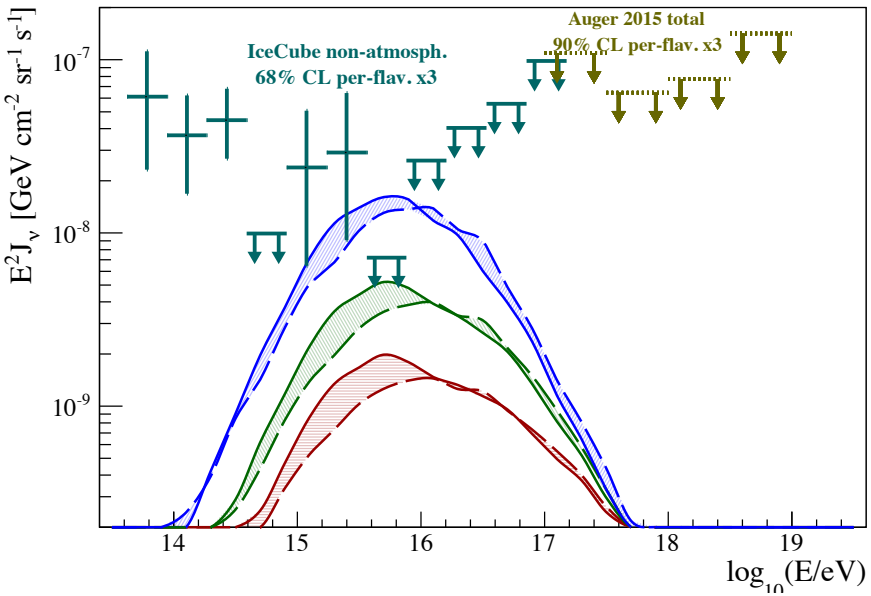
Berezinsky and Blasi (2012)



Roulet, Sigl, van Vliet, Mollerach (2013)

ν spectra – Mixed composition model

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

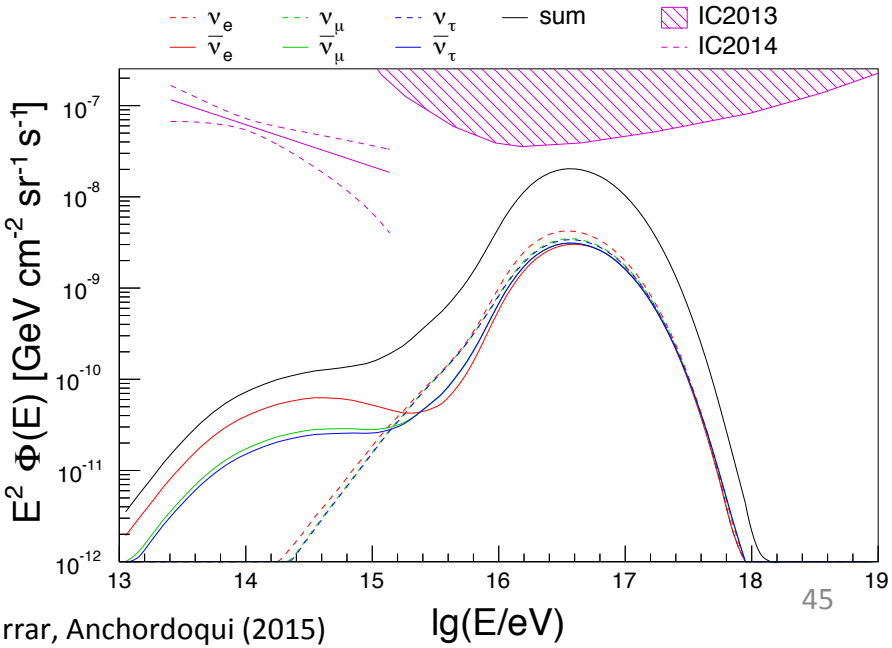


✓ EeV neutrinos

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 only in the case of strong cosmological evolution (AGN like).



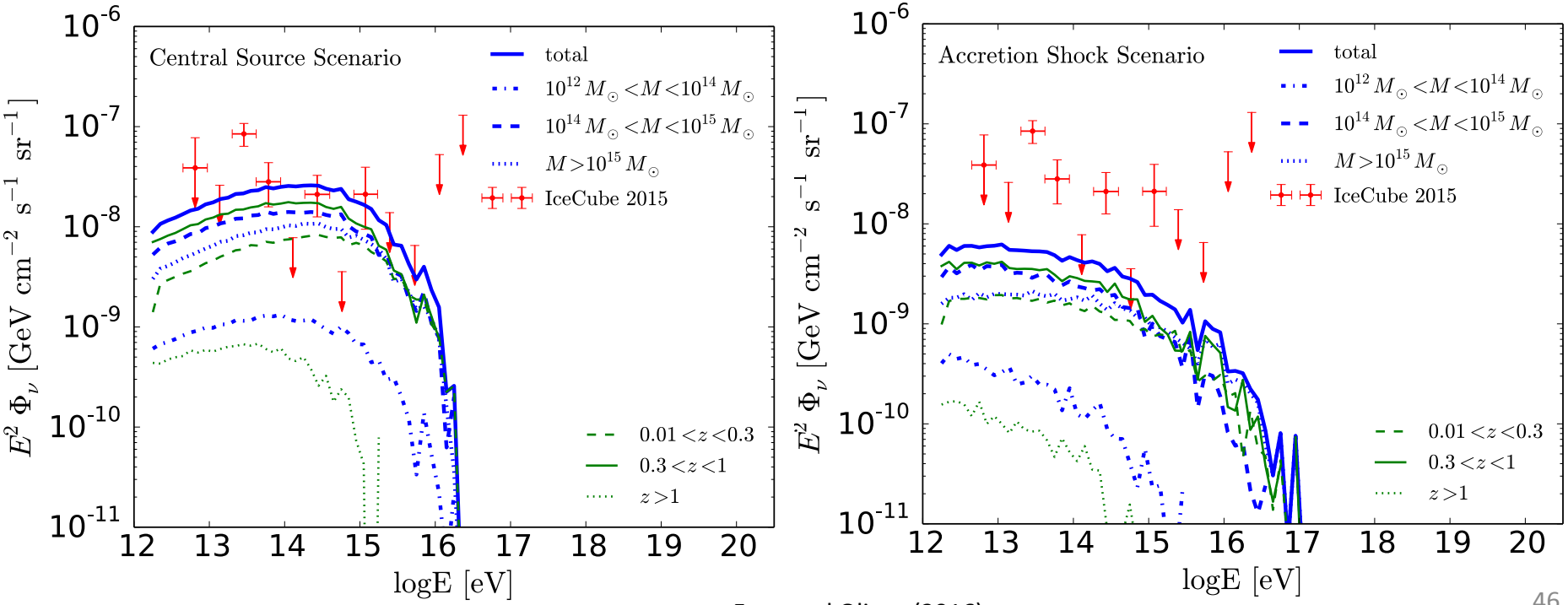
Unger, Farrar, Anchordoqui (2015)

Neutrinos from Clusters of Galaxies

- ✓ Because of their magnetic fields (at several μG level) clusters of galaxies are "storage rooms" for cosmic rays till energies ~$10^6 \div 10^8$ GeV, depending on the magnetic field turbulence.

Berezinsky, Blasi and Ptuskin (1998)

- ✓ Depending on the CR acceleration mechanism inside clusters, pp and pγ interactions can account for the observed IceCube neutrino flux at energies larger than 10^{12} eV.



Fang and Olinto (2016)