First CTAO Summer School

Radiation Processes in High Energy Nonthermal Universe

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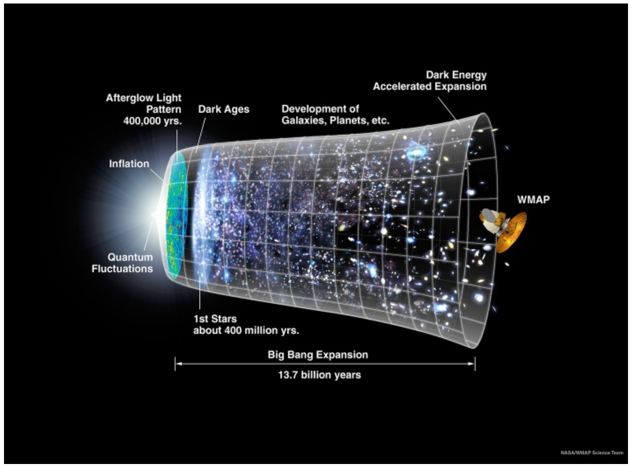
Nonthermal Relativistic Plasma ("Cosmic Rays"): the 4th substance of visible Universe



in the framework of Big Bang Theory

the Universe is a *high energy phenomenon*

- its birth was an incredibly energetic event
- quite a long time it was "hot soup" consisting of thermal relativistic particles and radiation

2.7 K MBR ($\sim 10^{-3}$ eV) as relic of the primordial "soup"

presently Universe is cold but production of relativistic particles continues in

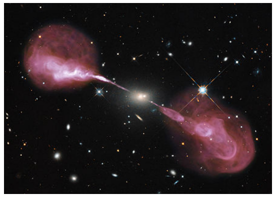
Cosmic Ray Factories - particle accelerators producing the 4th substance of the visible Universe - after *matter, radiation and magnetic fields*

Relativistic Nonthermal Plasma or "Cosmic Rays"

can be directly probed by cosmic electromagnetic radiation from MHz Radio to PeV gamma rays two comments

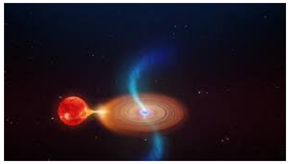
high energy phenomena - *not necessarily high energy (γ) radiation*

Synchrotron MHz/GHz radio emission of sub to multi-GeV electrons hystorically was the first window on nonthermal/high-energy Universe

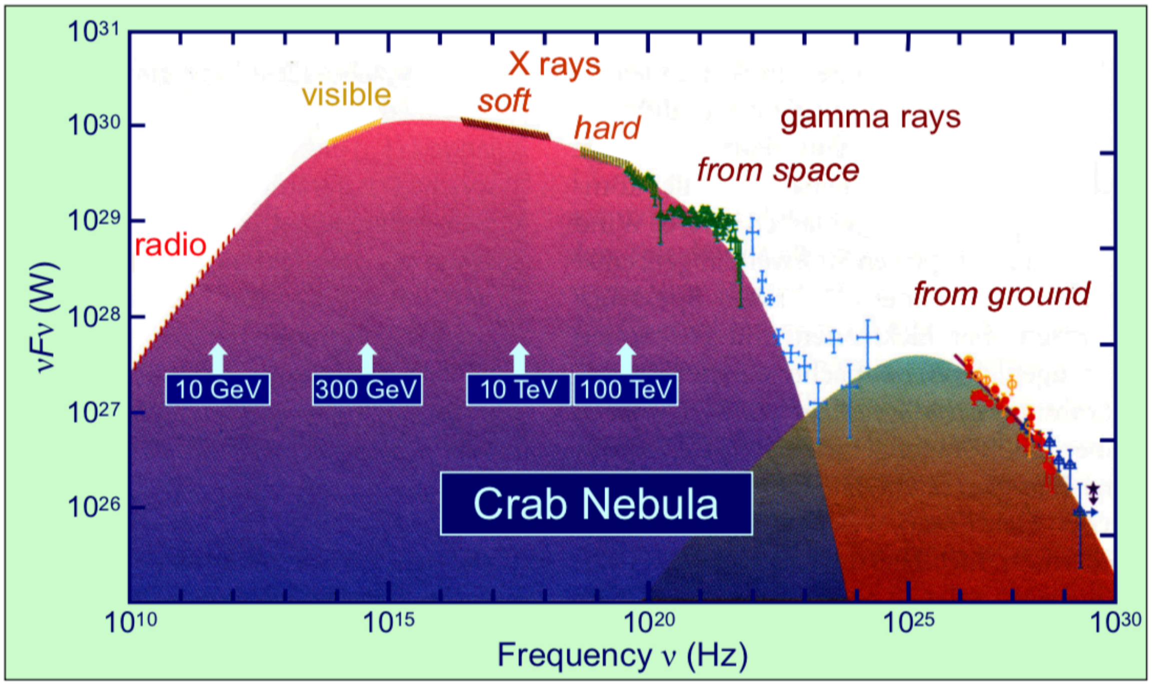


γ-rays - *not necessarily of non-thermal origin*

plasma accreting onto black hole closer to event horizon could be heated to temperatures 10^{11} - 10^{12} K - characteristic thermal radiation in the γ-ray band



a non-thermal astrophysical object seen over 20 energy decades



R, mm, IR, O, UV,X

gamma-rays

FA & AA 1996

nonthermal cosmic radiation: *not only gamma-rays*

Synchrotron emission from Radio through IR/optical/UV to X-rays

MHz- GHz Radio in ISM, Radiogalaxies, … - MeV to GeV electrons

slow process, but effective

X-rays in SNRs and PWNe > 100 TeV electrons
Blazars and GRBs > 0.1 TeV electrons

extremely fast and effective processes

Nonthermal X-ray bremsstrahlung > 1 keV electrons
> 100 MeV protons

inefficient mechanism - nevertheless, it works in some objects, e.g. during solar flares

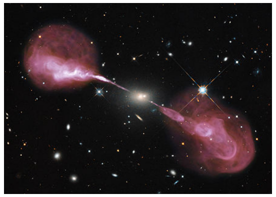
Thermal (often comptonized) X-ray bremsstrahlung $kT > 10^7$ K

extremely effective in SNRs, Galacy Clusters, accretion disk around Black Holes,…

two comments

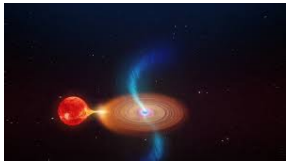
high energy phenomena - *not necessarily high energy (γ) radiation*

e.g. radio emission of synchrotron radiation of sub to multi-GeV electrons until recently was the main window on nonthermal/high-energy universe



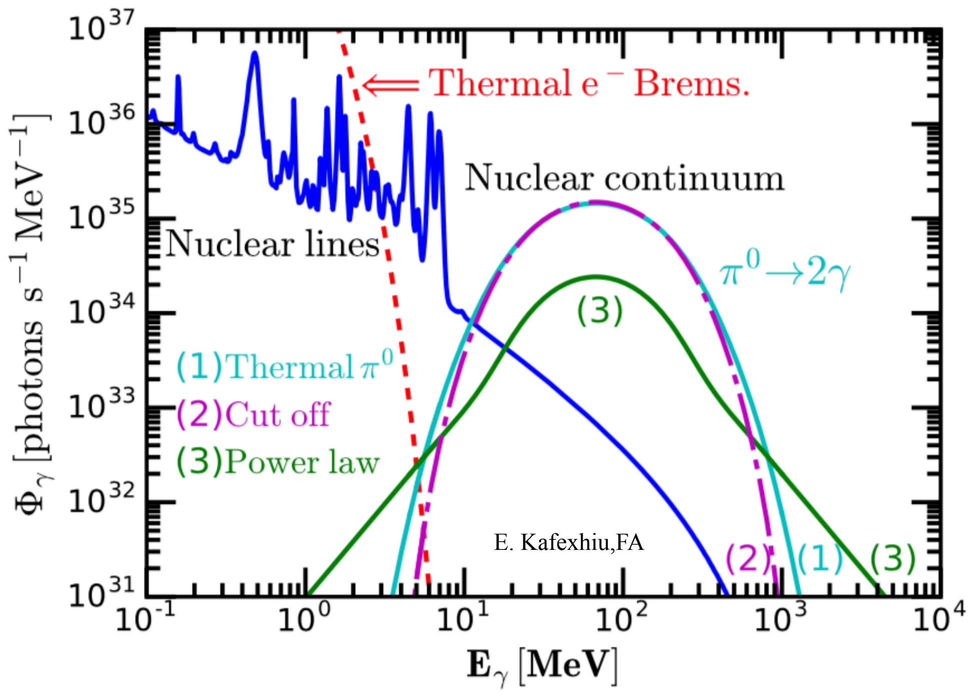
high energy γ-rays - *not necessarily imply non-thermal origin*

e.g. plasma accreting onto black closer to event horizon could be heated to temperatures 10^{11} - 10^{12} K - characteristic thermal radiation in the γ-ray band



Gamma-ray emission of hot two-temperature thermal plasma formed at accretion of gas onto a 10 solar masses black hole

microquasar



unique measure of the ion temperature in the accretion flow close to the gravitational radius

gamma ray line production - two orders of magmitude higher than the case of CRs interactingg with cold gas but still very low - less than 10^{-4} - to be deteted by current detectors more comments

Maxwellian (type) particle distribution *- not necessarily thermal*

when interpreting γ-ray spectra sometimes we need a Maxwellian type distribution. It does not mean, however, that we see the emission of thermal plasma. Some specific ("stochastic" or Fermi II type) mechanisms of particle acceleration can lead to a Maxwellian type distributions of particles

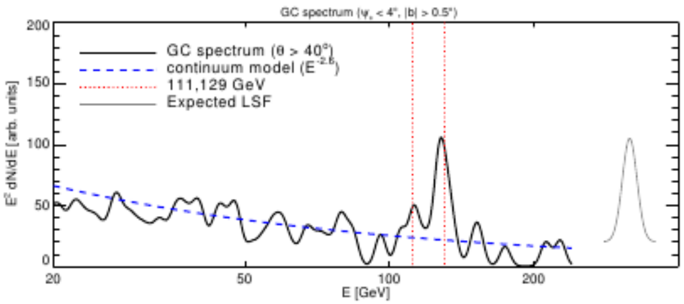
Sources of nonthermal emission *- do not necessarily coincide with accelerators*

nonthermal emission is a result of interaction of a beam of relativistic particles with a target (gas, B-field, photons), therefore the emission source (= target) and the accelerator can be separated

Dark Matter as "smoking gun " ? *- often invoked to explain unusual/irregular features revealed by observations but in most cases unnecessary exaggeration*

such strong claims in the context of one of the most fundamental objectives of modern physics and astrophysics require a careful judgment through the "Occam's razor" principle, i.e. exploration of other more conventional (and natural) interpretations example

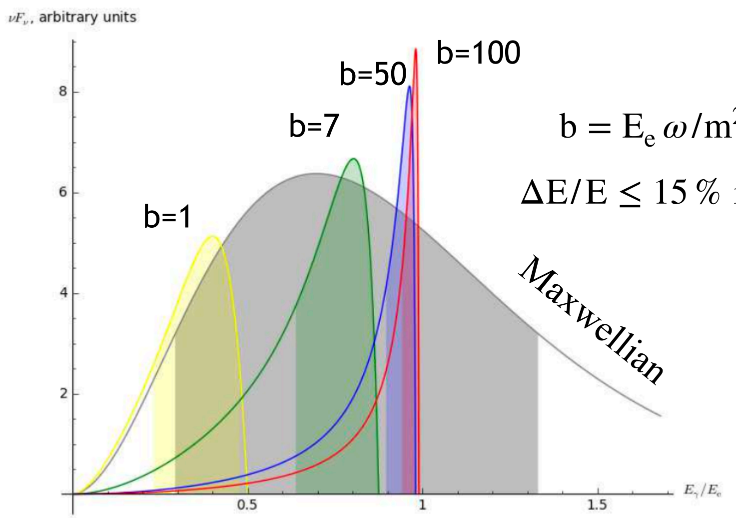
narrow GeV/TeV gamma-ray lines: astrophysical or DM origin?



DM origin as the only option?

~130 GeV gamma-ray line detected by Fermi LAT? *

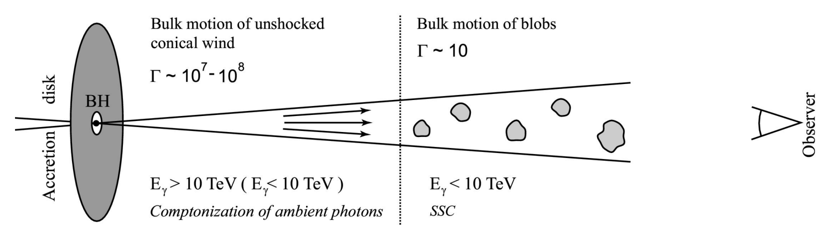
NO - it can be explained as Inverse Compton scattering of monoenergetic electrons and cold ultra relativistic (e.g.) pulsar winds in the deep Klein-Nishina regime



$b = E_e\,\omega/m^2c^4$

$\Delta E/E \le 15\,\%$ if $b \ge 30$

often confusion between acceleration of bulk motion and particle acceleration !



b >> 1 - distribution of target photons - *not important*
distribution of electrons - *important* =>
we need monoenergetic electrons.
A cold ultrarelativistic pulsar wind?

* later not confirmed

High Energy Gamma Rays (neutrinos) as unambiguous signatures of non-thermal ultra-relativistic processes and phenomena

gamma-ray energy bands

LE	or	MeV :	0.1 -100 MeV
HE	or	GeV :	0.1 -100 GeV
VHE	or	TeV :	0.1 -100 TeV
UHE	or	PeV :	0.1 -100 PeV
EHE	or	EeV :	0.1 -100 EeV

$1\,\text{MeV} = 10^6\,\text{eV}, \; 1\,\text{GeV} = 10^9\,\text{eV}, 1\,\text{TeV} = 10^{12}\,\text{eV}, \; 1\,\text{PeV} = 10^{15}\,\text{eV},$

low bound - nuclear gamma-rays, upper bound - highest energy cosmic rays

although the production of gamma rays inevitably occurs at every point in the Universe, conservative ("realistic") estimates of the detectability of gamma-ray sources in the past, especially at VHE/UHE, have not been very optimistic or encouraging.

today we have **thousands of GeV**, **hundreds of TeV**, **tens of PeV** **detected** sourcers reprsenting 15+ source populations - **a pleasant surprise**!

VHE and UHE TeV emitters have representing

- SNRs, Stellar Clusters, GMCs
- Pulsars, Pulsar Winds (?), PWNe , Pulsar Halos
- Binaries - Novae, Binary Pulsars, Microquasars
- Galaxies, Starburst Galaxies,
- Radiogalaxies,
- AGN,
- GRB afterglows

not all of them contribute to local CR flux but all are linked to

Particle Accelerators - factories of relativistic matter

TeVatrons and PeVatrons

discovery of hundreds VHE/UHE γ-ray emitters reprsenting 15+ source populations over the last two decades, is a remarkable achievement with a *surprise outcome*:

=> Universe is full of **TeVatrons**

surprise continues ...

over the last 1-2 years - discovery of tens of UHE γ-ray sources in Milky Way
=> the Galaxy is full of **PeVatrons**

analogy with X-rays?
as cosmic plasmas are **heated** up to keV temperatures - almost everywhere,
electrons/protons are accelerated to TeV/PeV energies - *almost everywhere*!

Protons and electrons are accelerated in different environments and on different scales at incredibly high acceleration rates and energy conversion efficiencies

not all of them contribute to local CR flux but all are linked to

Tevatrons/Pevatrons - super efficient factories of Ultrarelativistic Matter producing electons and protons to TeV/PeV energies

Effective Accelerators and Effective Emitters

gamma-ray source can be detected if they are produced with *high efficiency* in proximity of *powerful particle accelerators*

for a gamma-ray energy flux $F_{-12} = F_\gamma / 10^{-12}\,\mathrm{erg/cm^2\,s}$
luminosity of isotropic emitters should be

$$L_\gamma = 4\pi d^2 \simeq 10^{32}\ F_{-12}\,(d/1\,\mathrm{kpc})^2\,\mathrm{erg/s} \qquad \text{galactic scales}$$
$$\simeq 10^{44}\ F_{-12}\,(d/1\,\mathrm{Gpc})^2\,\mathrm{erg/s} \qquad \text{extragalactic scales}$$

this is the so-called *apparent* luminosity which could not coincide with *intrinsic* luminosity of beamed sources: $L_{int} = L_{app}\delta^{-4}$

distant EXG sources with fluxes significantly exceeding F_{-12} cannot be explained without invoking relativistic effects (Doppler boosting)

Detection of a gamma-ray source generally implies presence of a powerful particle accelerator(s) and favorable conditions for gamma-production - effective emitter(s)

Very Effective Accelerators

machines where acceleration proceeds with efficiency close to 100%

(i) fraction of available energy converted to nonthermal particles

in PWNe and perhaps also in SNRs and AGN *can be as large as 50 %*

(ii) maximum energy achieved by individual particles close to the maximum (theoretically) limit (“extreme accelerators)

gamma-ray production efficiency

many reported TeV gamma-ray sources require not only extreme particle accelerators but also effective production of gamma-rays

effective gamma-ray production?

cooling time of the given gamma-ray production process is shorter than

(1) timescales of radiative and non-radiative (e.g. adiabatic) losses
(2) intrinsic dynamical (source age, acceleration time, particle escape time)

Note: high efficiency is an important but not sufficient/decisive condition for a gamma-ray sources to be detected. The detectability depends also on

- ✓ power and distance to the source ($\sim W/d^2$)
- ✓ beaming factor, e.g. Doppler boosting ($\sim \delta^4$)
- ✓ Sensitivity of the instrument in the given energy domian

total energy in parent particles and power of the accelerator

$$W_{CR} = L_\gamma t_{rad} \qquad \dot{W}_{CR} = \kappa L_\gamma ; \ \kappa = t_{rad}/t_{dis} ; \ \kappa \geq 1 \ (\kappa \sim 1 \ - \ \text{calorimeter})$$

be careful with the interpretation of W_{cr} and $\dot{W}_{cr}$: we could miss γ-ray emission from extended emission regions because of the reduced brightness where κ could be different - typically, much smaller

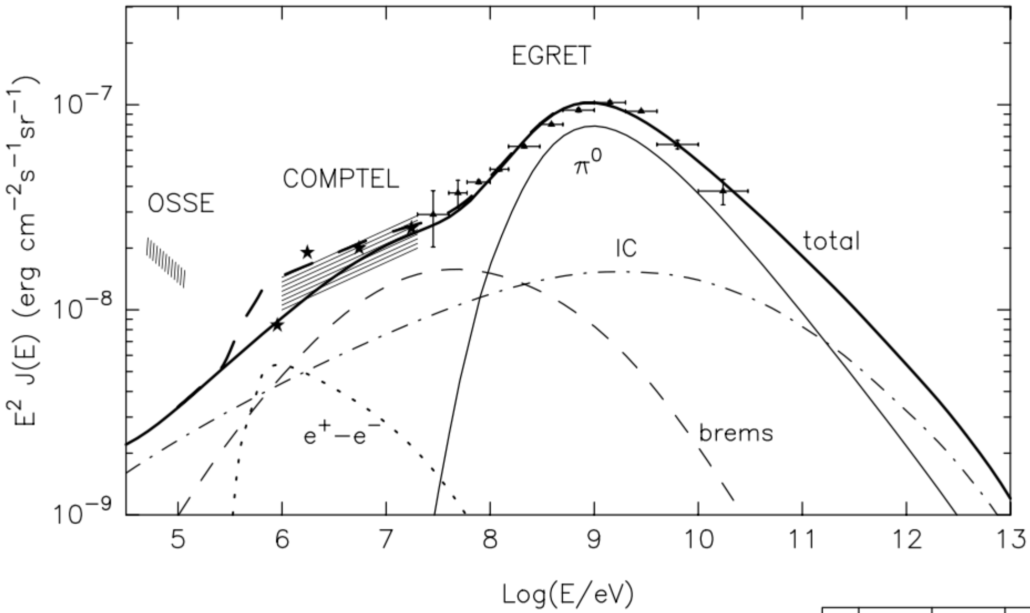
radiation and absorption processes

any interpretation of an astronomical observation requires

- ✓ *unambiguous identification of radiation mechanisms*
- ✓ *good knowledge of radiation and absorption processes*

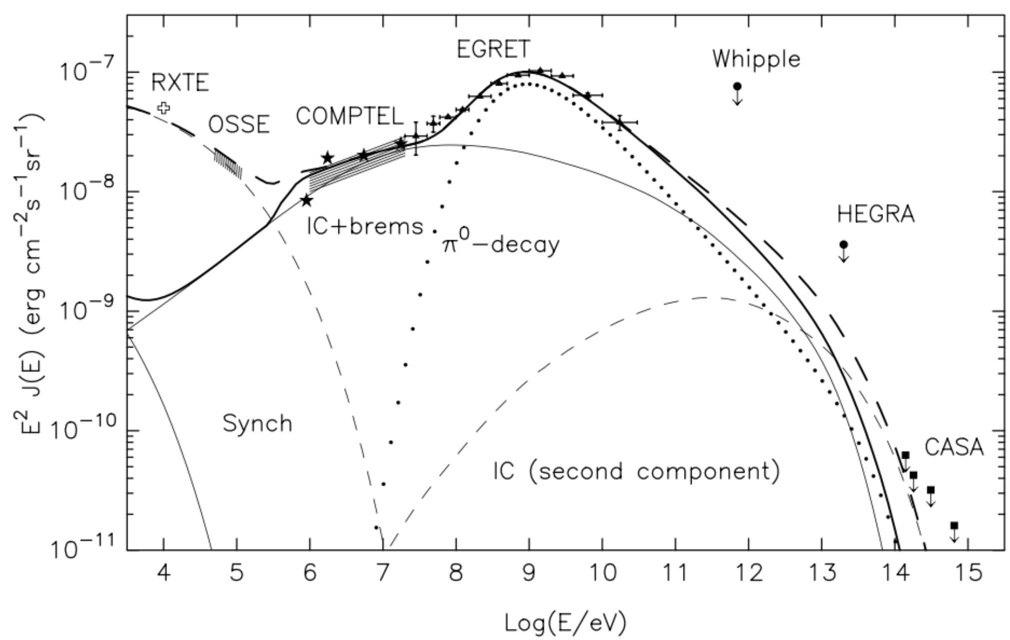
gamma-ray production and absorption processes:

several but well studied experimentaly and theopretically



combination of several radiation mechanisms contributing to diffuse galactic (background) radiation

from 10^5 to10^{15} eV



FA, Atoyan 2000

extreme physical conditions

generally, phenomena relevant to HEA generally proceed under extreme physical conditions in environments characterized with

- *huge gravitational, magnetic and electric fields,*
- *very dense background radiation,*
- *relativistic bulk motions (black-hole jets and pulsar winds)*
- *shock waves, highly excited (turbulent) media, etc.*

although at these conditions the interaction "standard" cross-sections generally remain valid, the γ-ray production and absorption processes may proceed essentially differently compared to the laboratory experiments

interactions with matter

E-M:

bremsstrahlung: e N(e) => e' γ N (e) $\quad < E_\gamma > \sim 1/2\ E_e$

pair production γ N(e) => e^+e^- N (e) $\quad E_\gamma \geq 2m_e^2$

e+e- annihilation e^+e^- => $\gamma\ \gamma$ (511 keV line) .

+continuum (before thermalization)

Strong/week: pp (A) => π, K, Λ, …

π, K, Λ => γ, ν, e, μ $\quad < E_\gamma > \sim 0.1\ E_p$

μ => ν

at low energies

Nuclear: p A => A* => A' γ, n

n p => D γ (2.2 MeV line)

interactions with radiation and magnetic fields

radiation

E-M

inverse Compton: $e\,\gamma\,(B) \Rightarrow e'\,\gamma$

$< E_\gamma > \sim \omega\,(E_e/m_c 2)^2$ T - regime

$\sim E_e$ KN - regime

$\gamma\gamma$ pair production $\gamma\,\gamma\,(B) \Rightarrow e^+e^-$

$E_\gamma\,\omega \geq 2m_e c^2$

Strong/week

$p\,\gamma \Rightarrow \pi, K, \Lambda, \ldots$

$\pi, K, \Lambda \Rightarrow \gamma, \nu, e, \mu$

$\mu \Rightarrow \nu$

$A\,\gamma \Rightarrow A* \Rightarrow A'\,\gamma$

$< E_\gamma > \sim 0.1\ E_p$

$< E_\gamma > \sim 0.001 A^{-1} E_\gamma$

B-field

magnetobremsstrahlung

synchrotron $e\,(p)\,B \Rightarrow \gamma$

curvature

jitter

$< E_\gamma > \sim BE_e^2 \quad E_{\gamma,max} \sim \alpha^{-1}\,mc^2$

much higher in the jitter regime

pair production $\gamma\,B \Rightarrow e+e-$

$E_\gamma \geq (B/B_{cr})\ m_e c^2$

calculations of gamma-ray energy spectra and fluxes

one needs two functions:

differential cross-section

energy distribution of parent particles

Differential cross section:

$$\frac{d\sigma}{d\Omega}d\Omega = \frac{\text{number of particles scattered into solid angle } d\Omega \text{ per unit time}}{\text{incident flux}}$$

Integral cross section:

$$\sigma_{\rm tot} = \int \frac{d\sigma}{d\Omega}d\Omega \qquad [\sigma_{\rm tot}] = {\rm cm}^2$$

Particle Distribution:

$$N(E,t) = \frac{\text{number of particles}}{\text{unit energy} \times \text{unit volume}}.$$

general kinetic equation that describes the evolution of particle distribution f(E,**r**,t) including the diffusion, convection, energy losses and the acceleration terms (e.g. Ginzburg & Sirovatskii 1964),

$$\frac{\partial f}{\partial t} = \nabla \cdot (D_r \nabla f) - \nabla \cdot (\mathbf{u}_r f) + \frac{\partial}{\partial E}(P_r f) - \frac{\partial}{\partial E}(b_r f) + \frac{\partial^2}{\partial E^2}(d_r f) \, .$$

in many cases the acceleration and radiation production regions are separated, then

$$\frac{\partial N}{\partial t} = \frac{\partial}{\partial E}(PN) - \frac{N}{\tau_{\rm esc}} + Q$$

where

$$N(E,t) \equiv \int f \, d^3 r$$

steady-state solution

$$N(E) = \left|\frac{dE}{dT}\right|^{-1} \int_E^\infty Q(E) \, dE$$

energy distibutions of particles

acceleration (injection) spectrum of particles; generally power-law with

$\dot{Q}(E) = \dot{Q}_0(E)E^{-\alpha}$ high-energy cutoff determined by the condition

"acceleration rate=energy loss rate" or $t_{acc}=t_{cool}$

later (in the gamma-ray production region) the particle energy spectrum is changed due to energy losses: $N(E) \propto (\mathrm{d}E/\mathrm{d}t)^{-1} \int_E Q(E)\mathrm{d}E$

the steady state solutions for power-law injection

$\frac{dE}{dt} \propto E : \quad N(E) \propto E^{-\alpha}$ (e.g. bremsstrahlung, pp, adiabatic) - no spectral change

$\frac{dE}{dt} \propto E^2 : \quad N(E) \propto E^{-(\alpha+1)}$ (e.g. synchrotron, IC (Tompson)) - steeper

$\frac{dE}{dt} \propto const : \quad N(E) \propto E^{-(\alpha-1)}$ (e.g. ionozation) -harder

$\frac{dE}{dt} \propto E^{-1} : \quad N(E) \propto E^{-(\alpha-2)}$ (e.g. IC Klein-Nishina) - much harder

6

γ-ray data tell us about energy spectra of parent particles in emitter zone(s) which may significantly deviate (deformed) from the acceleration spectrum

basic radiation processes

comprehensivelly studied and understood
experimentally and/or theoretically (phenomenologically)

key condition to derive unambiguous information about parent particles

particles - relativistic electrons, protons and nuclei

targets - gas, photon fields, magnetic fields

nature of interactions/decays - electromagnetic, strong, weak

leptonic or hadronic?

gamma-rays produced in interactions of electrons and protons/nuclei often are called leptonic and hadronic interactions

but it is more appropriate to call them as E-M (electromagnetic) and S (strong)

examples:

(i) synchrotron radiation of protons - pure electromagnetic process

interaction of hadrons without production of neutrinos

(ii) photon-photon annihilation => $\mu^+\mu^-$ => *neutronos, antineutrinos*

production of neutrinos by photons as parent particles

E-M are calculated with high accuracy and confirmed experimentally

S/W are well studied experimentally and explained theoretically

often several processes proceed together => cascades in matter, radiation and B-fields interactions with gas

Differential cross-sections of B-H processes

Bremsstrahlung

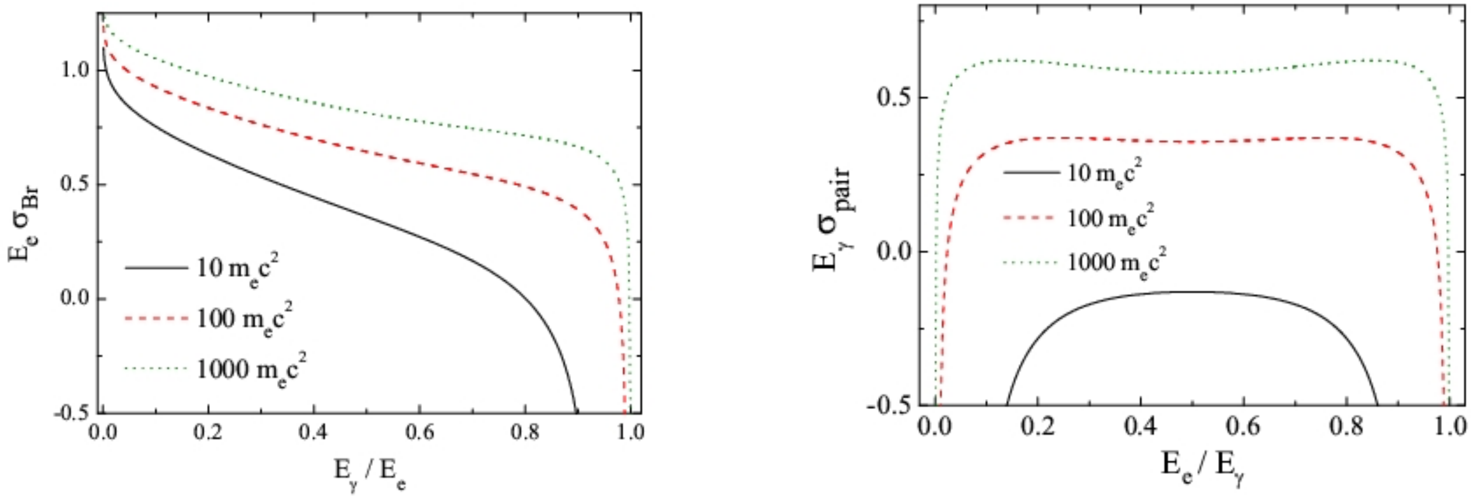
$$\sigma_{\mathrm{Br}}\left(E_\gamma, E_e\right) = 4\alpha r_e^2 Z^2 \frac{dE_\gamma}{E_e}\left\{\left[1+\left(1-\frac{E_\gamma}{E_e}\right)^2-\frac{2}{3}\left(1-\frac{E_\gamma}{E_e}\right)\right]\times \left[\ln\left(\frac{2E_e\left(E_e-E_\gamma\right)}{m_e c^2 E_\gamma}\right)-\frac{1}{2}\right]\right\}.$$

Pair-production

$$\sigma_{\mathrm{pair}}\left(E_\gamma, E_e\right) = 4\alpha r_e^2 Z^2 \frac{1}{E_\gamma}\left[\left(1-\frac{E_e}{E_\gamma}\right)^2+\left(\frac{E_e}{E_\gamma}\right)^2+\frac{2}{3}\left(1-\frac{E_e}{E_\gamma}\right)\frac{E_e}{E_\gamma}\right]\times \left\{\ln\left[\frac{2\left(E_\gamma-E_e\right)E_e}{m_e c^2 E_\gamma}\right]-\frac{1}{2}\right\},$$

$\alpha = 1/137,$ – fine structure constant, $\mathrm{r_e} = 2.8\times 10^{-13}\,\mathrm{cm}^2$ – electron radius 8

$\sigma_{\mathrm{T}} = \frac{8}{3}\pi \mathrm{r_e^2}$ – Thompson cross – section



Differential cross-sections normalized to $4\alpha r_e^2$

two processes together effectively support E-M cascades in cold matter

while pair-production generally does not play a significant role, the inverse Bethe-Heitler process can be critically importantfor highest energy cosmic rays

$$\alpha = 1/137, - \text{fine structure constant}, \quad r_e = 2.8 \times 10^{-13}\,\text{cm}^2 - \text{electron radius}$$

$$\sigma_T = \frac{8}{3}\pi r_e^2 \; - \; \text{Thompson cross - section}$$

some basic features of bremsstrahlung

cooling time: $t_{\rm br} = \frac{\varepsilon_{\rm e}}{-{\rm d}\varepsilon_{\rm e}/{\rm d}t} \simeq 4 \times 10^7 (n/1\ {\rm cm}^{-3})^{-1}\ {\rm yr}$

spectrum of γ-rays from a single electron: $1/E_\gamma$

power-law distribution of electrons: $N(E_e) \propto E_e^{-\alpha}$

γ-ray spectrum: $J(E_\gamma) \propto E_\gamma^{-\alpha}$ repeats the shape of electrons!

an example: *interstellar medium:* electron injection spectrum $Q(E_e) \propto E_e^{-\alpha_0}$

(1) at low energies $\alpha=\alpha_0-1$ because losses are dominated by ionization

(2) at intermediate energies $\alpha=\alpha_0$ because losses are dominated Bremsstrahung

(3) at very high energies $\alpha=\alpha_0+1$ because losses are dominated Synch./IC

annihilation of electron-positron pairs

astrophysical significance of this process - formation of $m_e c^2$=0.511MeV line gamma-ray emission at annihilation of thermalized positrons

however if positrons are produced with relativistic energies, a significant fraction - 10 to 20 % of positrons annihilate in flight before they cool down to the temperature of the thermal background gas (plasma)

power-law spectrum of positrons $E_+^{-\Gamma}$ => $J_{\rm ann}(E_\gamma) \propto E_\gamma^{-(\Gamma)}\,[\ln(2E_\gamma)-1]$

total cross-section: $\sigma_{\rm ann} = \frac{3}{8}\sigma_{\rm T}^2 E_+^{-1}[\ln(2E_+)-1]$

cooling time: $t_{\rm ann} = \frac{8}{3\sigma_{\rm T}^2 cn}\frac{E_+}{\ln(2E_+)-1} \simeq 4\times 10^6 \frac{E_+}{\ln(2E_+)-1}(n/1\ {\rm cm}^{-3})^{-1}\ {\rm yr}$

at energies $E \leq 0(\alpha_f^{-1} m_e c^2) \sim 15{\rm MeV}$ annihilation dominates over bremsstrahlumg

11

pp -> π^0 -> $\gamma\gamma$ - *a major gamma-ray production mechanisms*

relativistic protons and nuclei produce high energy in inelastic collisions with ambient gas due to the production and decay of secondary particles

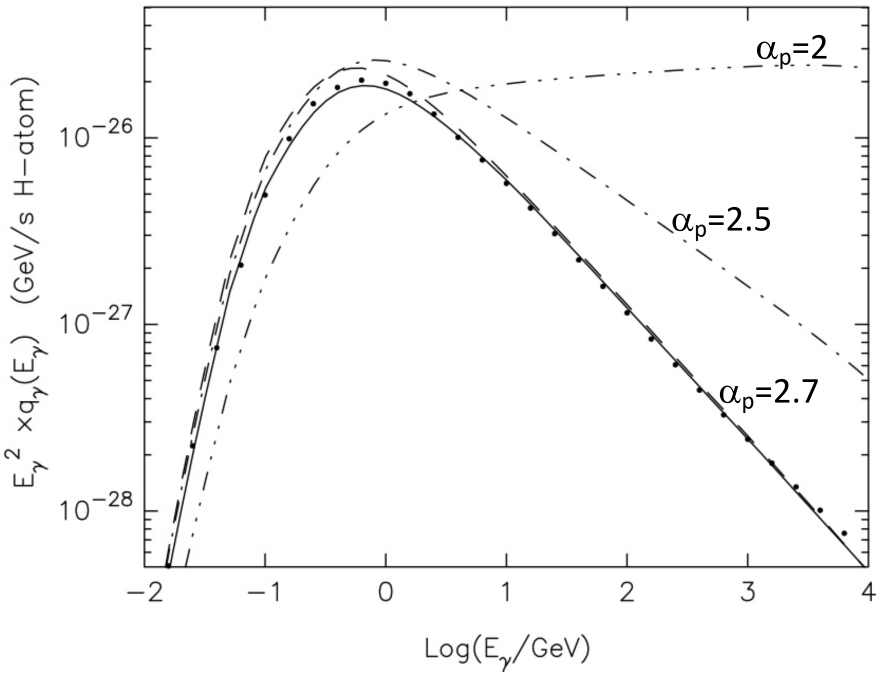
pions, kaons and hyperons

neutral π^0-mesons provide the main channel of gamma-ray production

- production threshold $E_{\rm th} = 2m_\pi c^2(1 + m_\pi/4m_{\rm p}) \approx 280$ MeV
- the mean lifetime of π^0-mesons $t_{\pi^0} = 8.4 \times 10^{-17}$ s
- three types of pions are produced with comparable probabilities
- spectral form of pions is generally determined by number of a few (one or two) leading particles (carrying significant fraction of the nucleon energy)
- cooling (radiation) time: $t_{pp} \sim 10^{15}\,(n/1\,{\rm cm}^{-3})^{-1}$ s

12

the π^0-deacy bump at $m_\pi c^2/2$ = 67.5 MeV (in diff. spectrum)



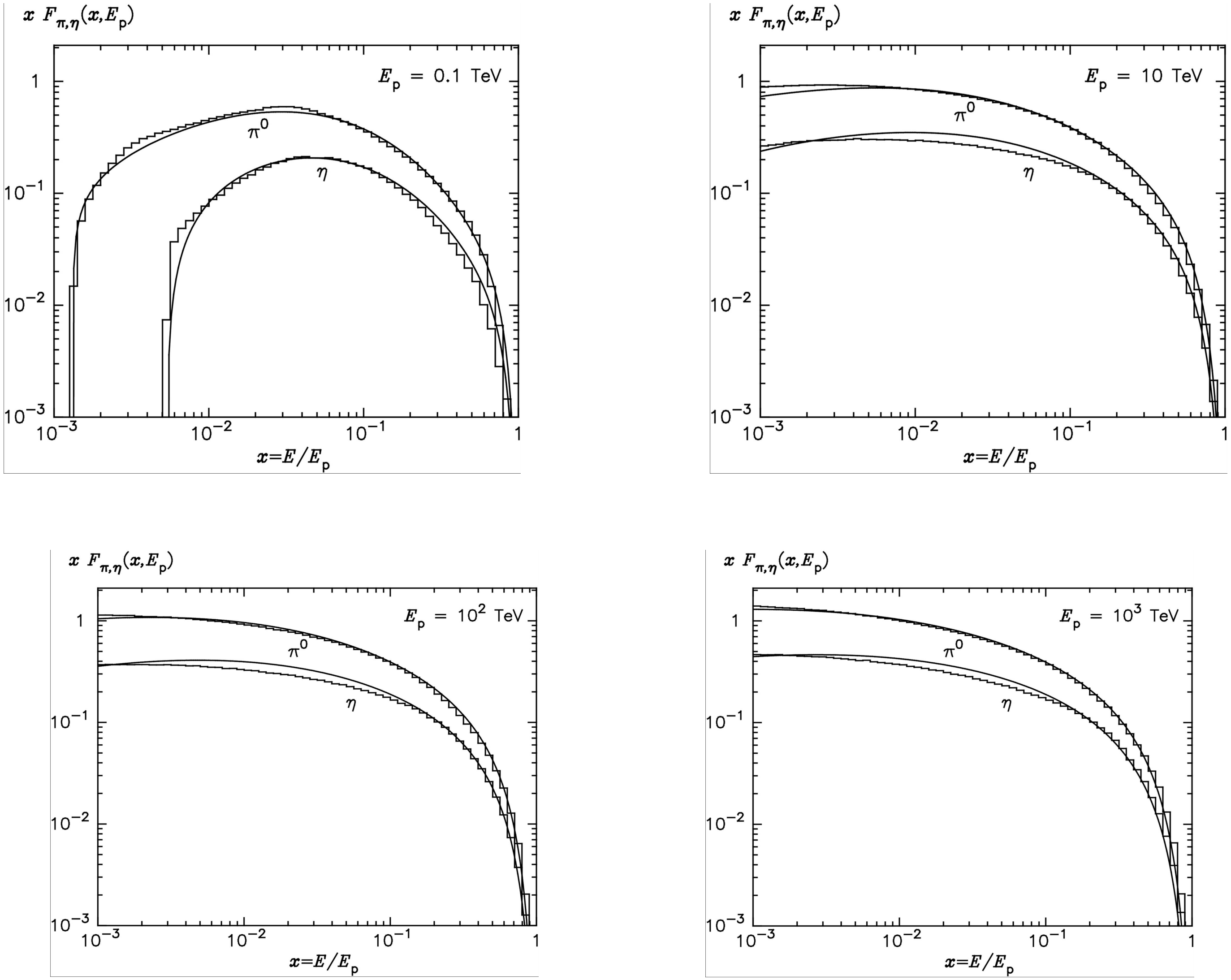
in the $E_\gamma^2\, q(E_\gamma)$ or νF_ν presentation the "bump" is shifted to ~1-2 GeV or disappears if $\alpha_p \leq 2$

for proton spectra - power-law without cutoff - delta-functional approximation works well for pi-mesons, and very good for gamma-rays since $\pi \rightarrow \gamma\gamma$ kinematics dominates in the formation of gamma-ray spectra (assuming that 0.17 fraction of the proton energy is channeled into pi-0 mesons

$$q_\gamma(E_\gamma) = 2\int_{E_{\min}}^{\infty} \frac{q_\pi(E_\pi)}{\sqrt{E_\pi^2 - m_\pi^2 c^4}} \mathrm{d}E_\pi$$

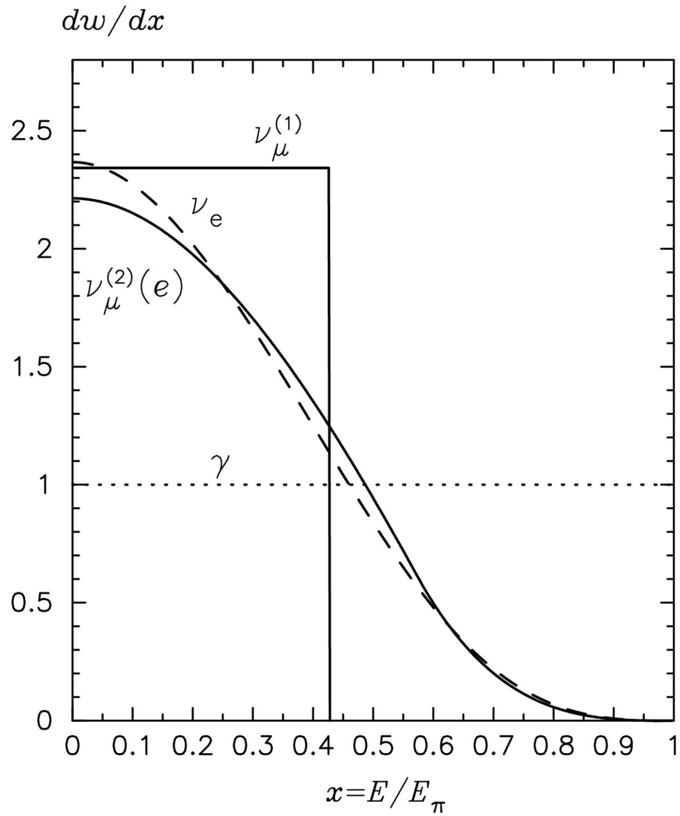
$$E_{\min} = E_\gamma + m_\pi^2 c^4/4E_\gamma$$

$$\begin{aligned} q_\pi(E_\pi) &= c\, n_{\mathrm{H}} \int \delta(E_\pi - K_\pi E_{\mathrm{kin}})\sigma_{\mathrm{pp}}(E_{\mathrm{p}}) n_{\mathrm{p}}(E_{\mathrm{p}})\mathrm{d}E_{\mathrm{p}} \\ &= \frac{c\, n_{\mathrm{H}}}{K_\pi}\sigma_{\mathrm{pp}}\left(m_{\mathrm{p}}c^2 + \frac{E_\pi}{K_\pi}\right) n_{\mathrm{p}}\left(m_{\mathrm{p}}c^2 + \frac{E_\pi}{K_\pi}\right) \end{aligned}$$

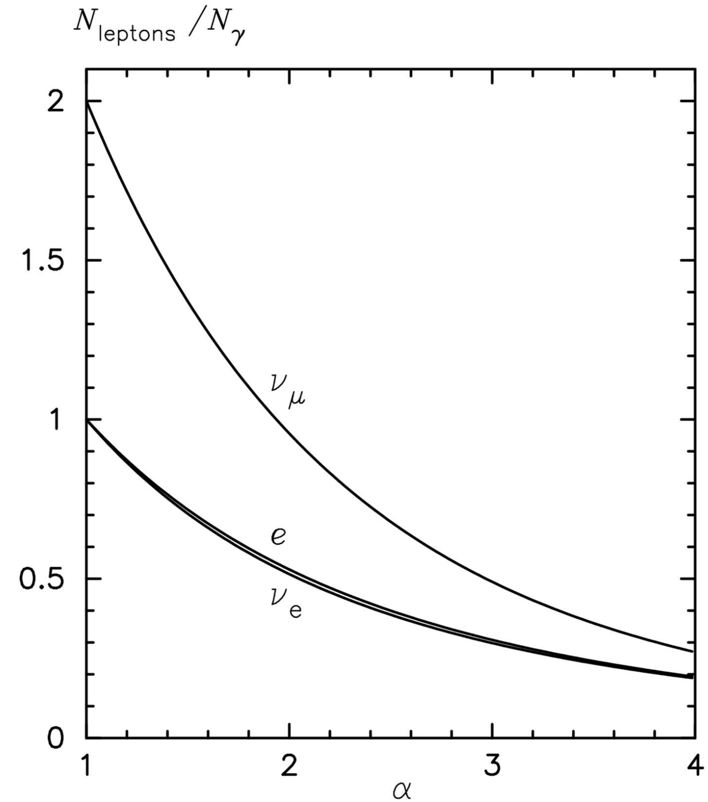


energy spectra of π- and ν mesons at proton-proton interactions

histograms – SIBYLL code, solid lines – analitical parametrization decay modes: $\pi^o \rightarrow \gamma\,\gamma$, $\pi^{+/-} \rightarrow \mu^{+/-}\ \nu_\mu$, $\mu^{+/-} \rightarrow e^{+/-}\ \nu_e\ \nu_\mu$



energy distributions of stable decay-producs – γ, ν_e, ν_μ



lepton/photon ratios for power-law energy distributions of p-mesons

15

γ: $F_\gamma(x,\,E_p) = B_\gamma \frac{d}{dx}\left[\ln(x)\left(\frac{1-x^{\beta_\gamma}}{1+k_\gamma x^{\beta_\gamma}(1-x^{\beta_\gamma})}\right)^4\right] =$

$$B_\gamma \frac{\ln(x)}{x}\left(\frac{1-x^{\beta_\gamma}}{1+k_\gamma x^{\beta_\gamma}(1-x^{\beta_\gamma})}\right)^4 \times \left[\frac{1}{\ln(x)} - \frac{4\beta_\gamma x^{\beta_\gamma}}{1-x^{\beta_\gamma}} - \frac{4k_\gamma \beta_\gamma x^{\beta_\gamma}(1-2x^{\beta_\gamma})}{1+k_\gamma x^{\beta_\gamma}(1-x^{\beta_\gamma})}\right],$$

$$B_\gamma = 1.30 + 0.14\,L + 0.011\,L^2\ , \quad \beta_\gamma = \frac{1}{1.79+0.11\,L+0.008\,L^2} \quad k_\gamma = \frac{1}{0.801+0.049\,L+0.014\,L^2}\ ,$$

e and $\nu_\mu^{(2)}$: $F_e(x,\,E_p) = B_e \frac{(1+k_e(\ln x)^2)^3}{x\,(1+0.3/x^{\beta_e})}\,(-\ln(x))^5\ ,$

$$B_e = (69.5 + 2.65\,L + 0.3\,L^2)^{-1}\,, \beta_e = \frac{1}{(0.201+0.062\,L+0.00042\,L^2)^{1/4}}, k_e = \frac{0.279+0.141\,L+0.0172\,L^2}{0.3+(2.3+L)^2}$$

$\nu_\mu^{(1)}$: $F_{\nu_\mu^{(1)}}(x,\,E_p) =$

$$B' \frac{\ln(y)}{y}\left(\frac{1-y^{\beta'}}{1+k'y^{\beta'}(1-y^{\beta'})}\right)^4 \times \left[\frac{1}{\ln(y)} - \frac{4\beta' y^{\beta'}}{1-y^{\beta'}} - \frac{4k'\beta' y^{\beta'}(1-2y^{\beta'})}{1+k'y^{\beta'}(1-y^{\beta'})}\right]$$

$$B' = 1.75 + 0.204\,L + 0.010\,L^2\,, \beta' = \frac{1}{1.67+0.111\,L+0.0038L^2}\,, k' = 1.07 - 0.086\,L + 0.002\,L^2\,.$$

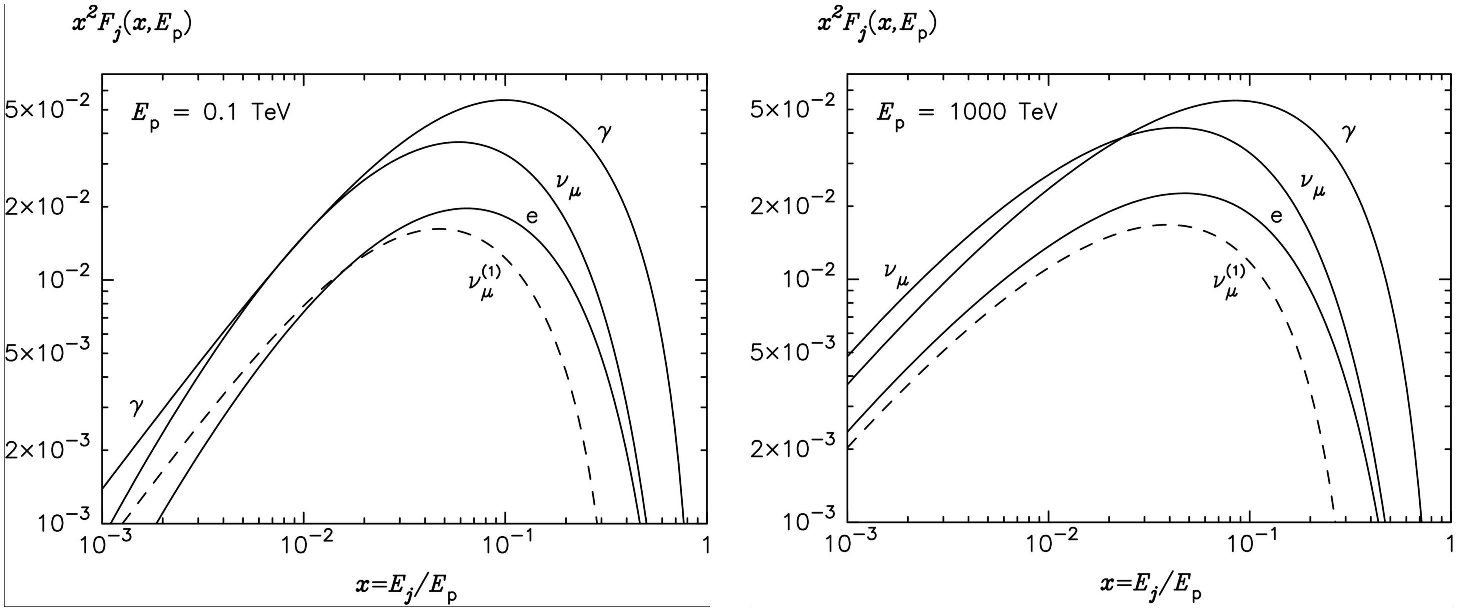
$$x = E_{\rm i}/E_p, \quad y = x/0.427, \quad L = \ln(E_p/1\,{\rm TeV})$$

accuracy: *better than 10 % within energy range of protons* $10^2 - 10^5$ GeV

Kelner et al. 2006

analytical presentations of energy spectra of γ, e, ν_μ

16

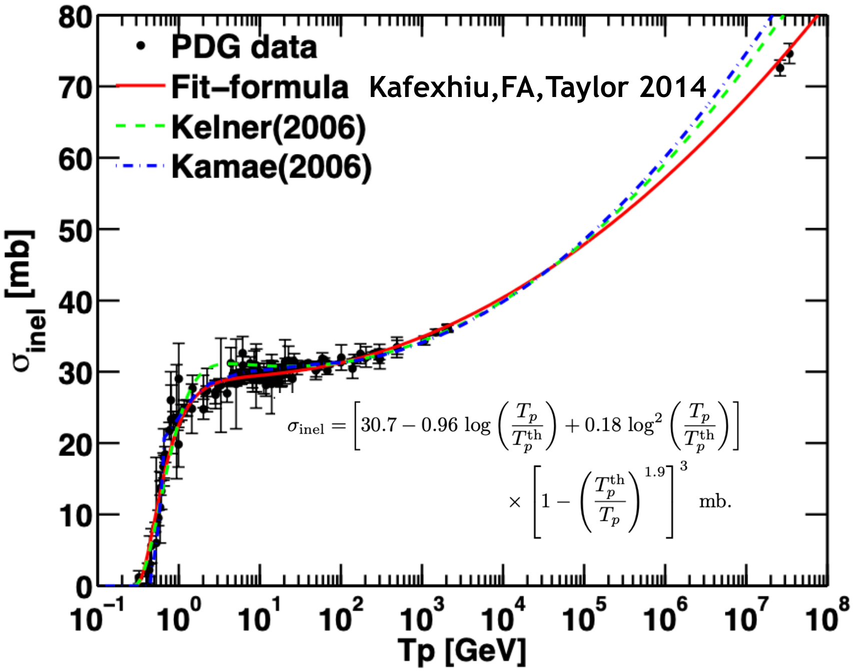


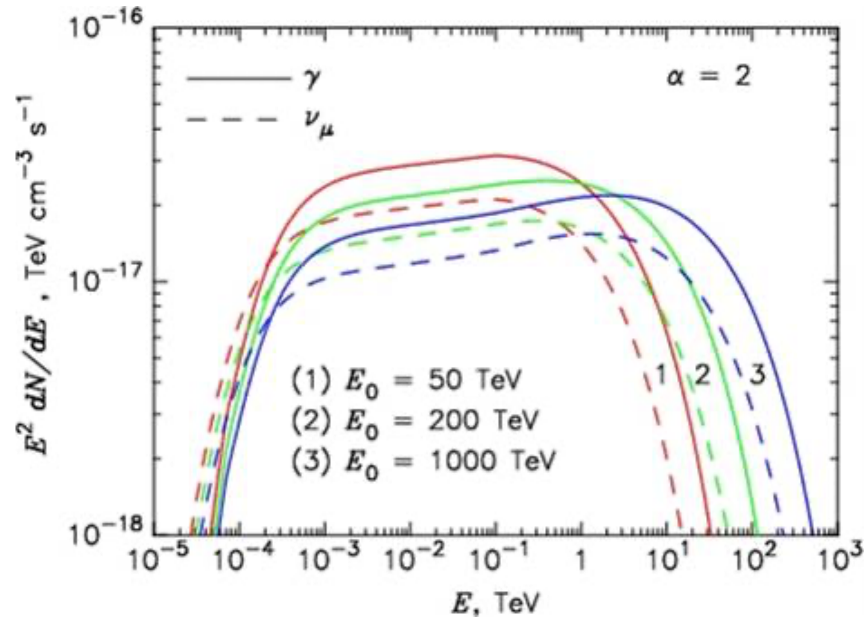
energy spectra of secondary gamma-rays, electrons and neutrinois

$\mathrm{E}_{\gamma,\max} \simeq 0.1\,\mathrm{E_p}$ then a cutoff; but cutoff is not very sharp up to $\simeq 0.5\,\mathrm{E_p}$

17

total inelastic pp cross-section and production rates of γ and νμ for power-law spectrum of protons $n_H w_p = 1 erg/cm^6$





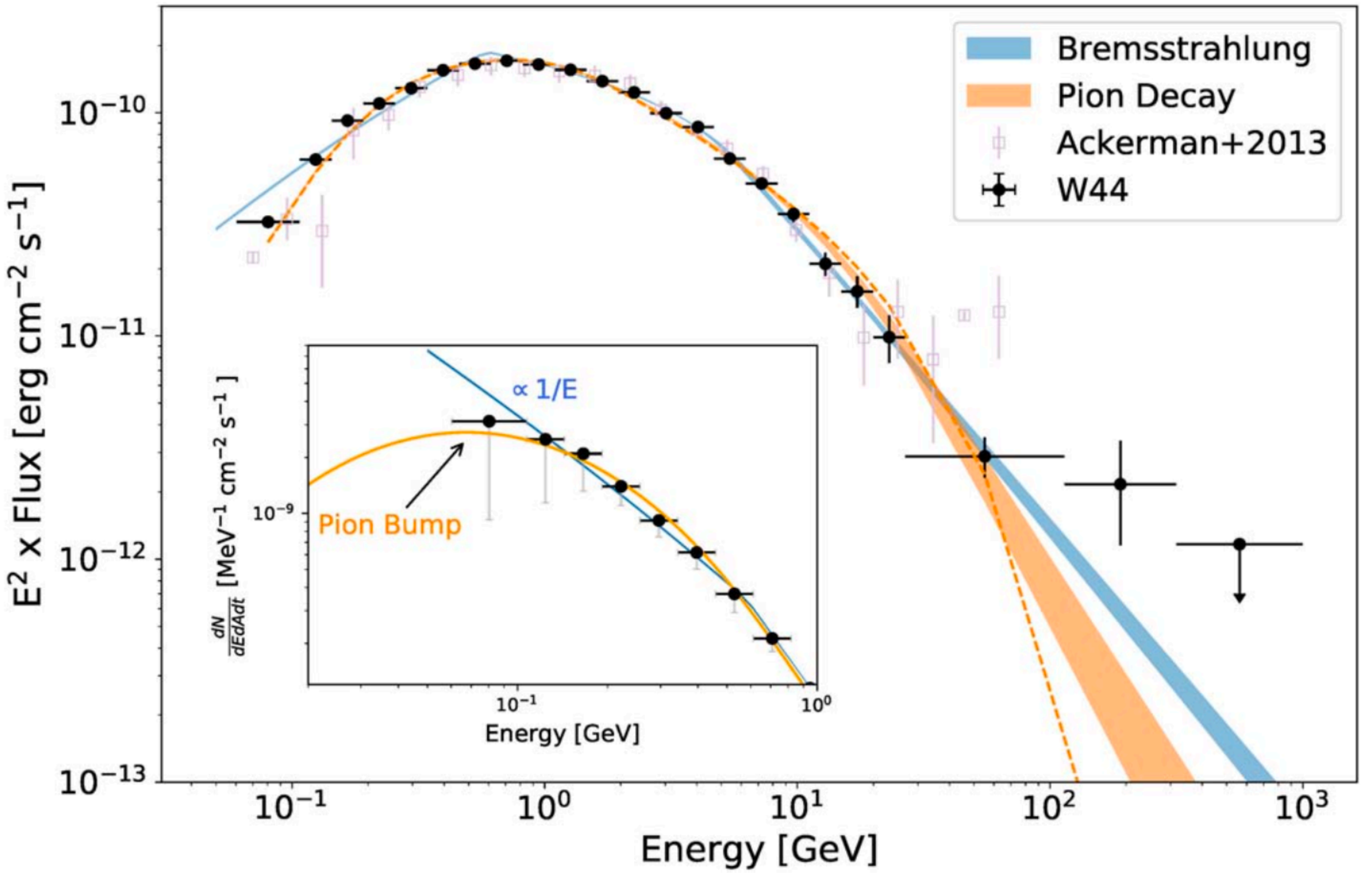
Two characterstic features:

For a power-law proton spectrum with a cutoff, $E^{-\alpha_p} \exp[-(E/E_{cut})]$

(1) the power-law part is a bit harder $\alpha_\gamma \approx \alpha_p - \Delta\alpha$; $\Delta\alpha \sim (0.05 - 0.1)$ 18

(2) the cutof is slower than in the proton spectrum; $E_\gamma^{-\alpha_\gamma} \exp[-(E/E_{cut})^s]$ with $s \sim 0.5$

Peron et al 2020



"π^0 -bump" identified in the spectrum of SNR W44!

interactions with photon fields
photon-photon pair production and Compton scattering

two processes are tightly coupled - both have large cross-sections and work effectively everywhere in the Universe from compact objects like pulsars, Black Holes and Active Galactic Nuclei to large scale structures as clusters of galaxies

IC - production process - no energy threshold
PP - $\gamma\gamma$ sorption process: threshold: $E_{\gamma 1} E_{\gamma 1} > m^2 c^4 (1-\cos\phi)^{-1}$

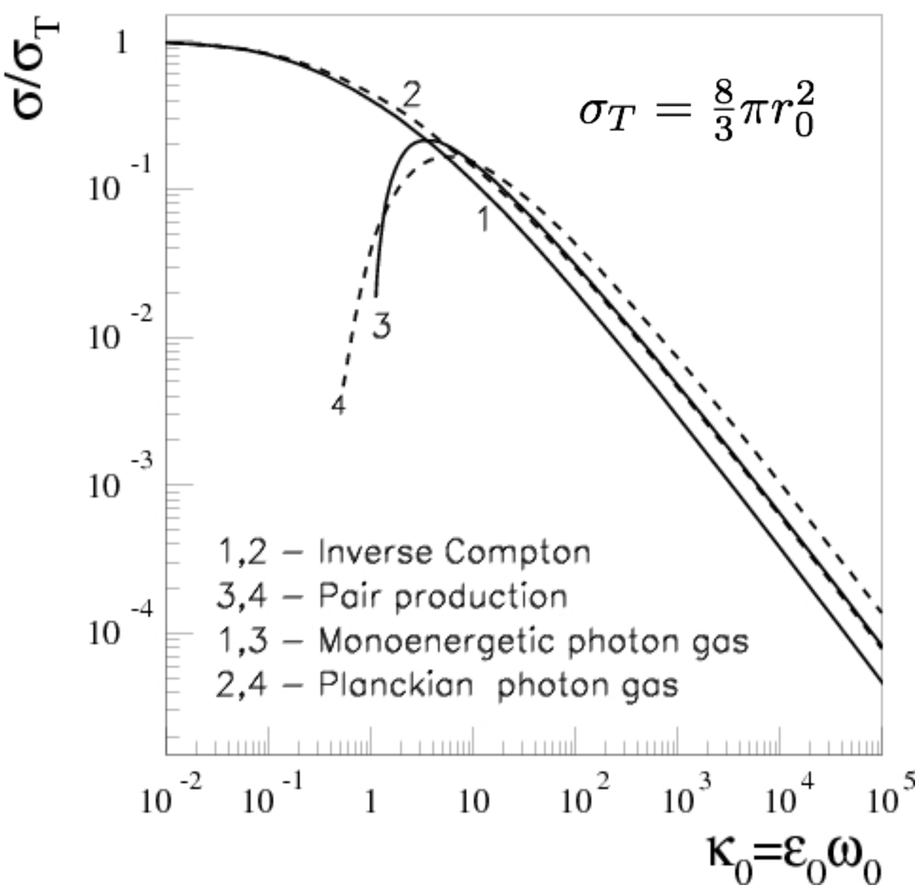
in radiation-dominated environments both processes work together supporting the transport of high energy radiation via electromagnetic

Klein-Nishin Cascades

if $B^2/8\pi \geq w_r$

only synchrotron radiation of the secondary electrons

integral cross-sections



maximum cross-section of pair-production at κ_0 ~4 or E_γ~1(ε/1eV)$^{-1}$ TeV

most effectively interact

MeV <=>MeV

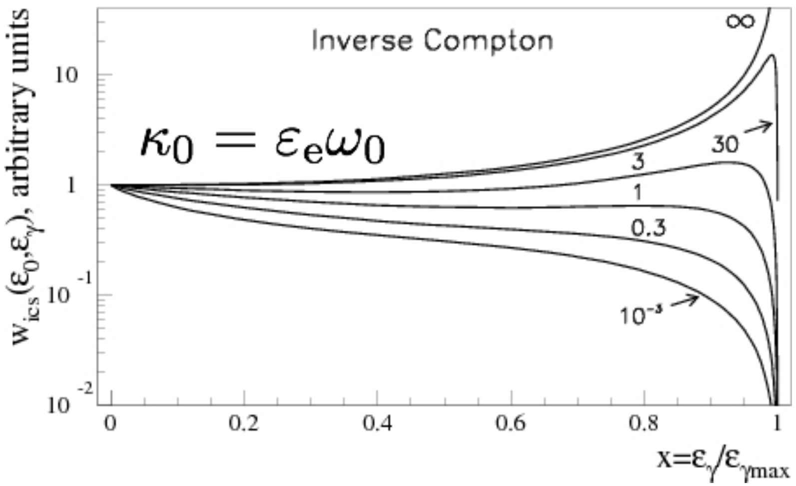
GeV <=> X

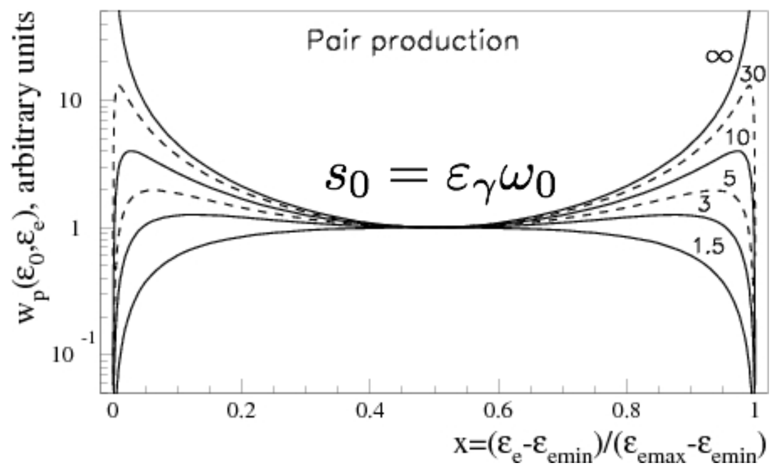
TeV <=> O

PeV <=> mm

EeV <=> R

differential cross-sections





$$\varepsilon_{\gamma\max} = 4\varepsilon_0(\kappa_0/1+4\kappa_0)$$

$$\varepsilon_{\mathrm{emin,\,emax}} = 0.5\varepsilon_0(1 \mp \sqrt{1-1/\kappa_0})$$

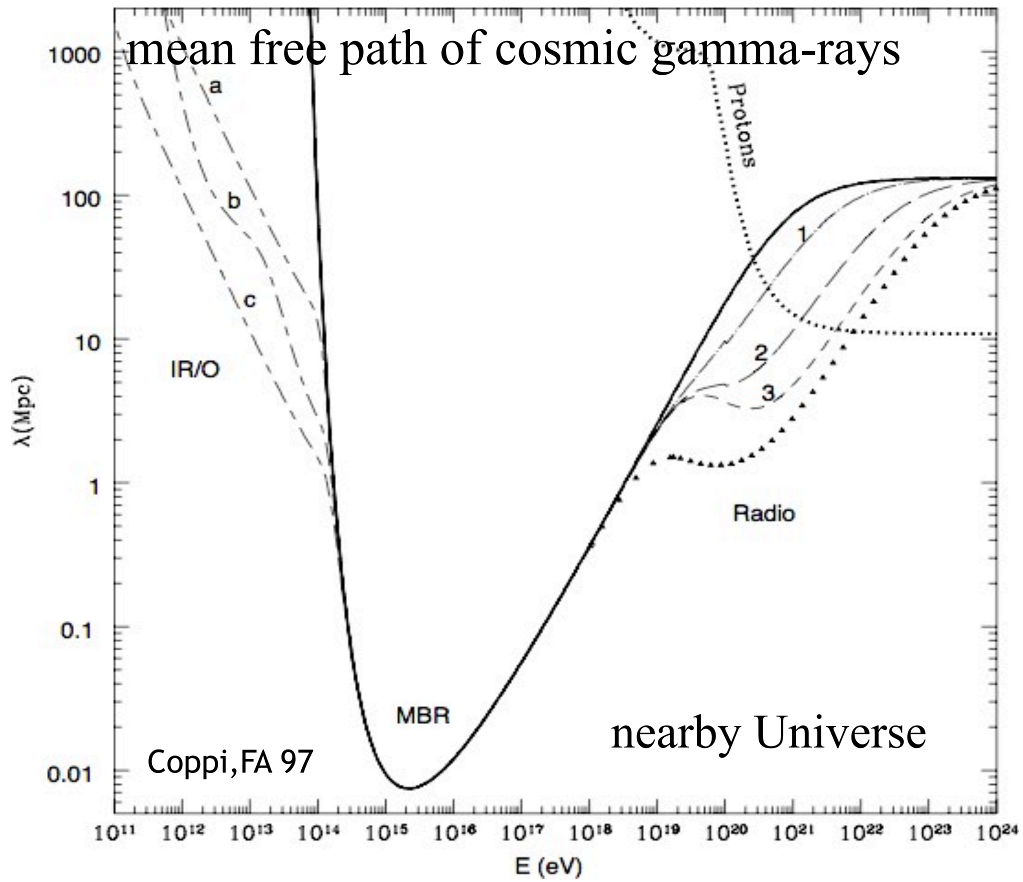
γ-ray horizon

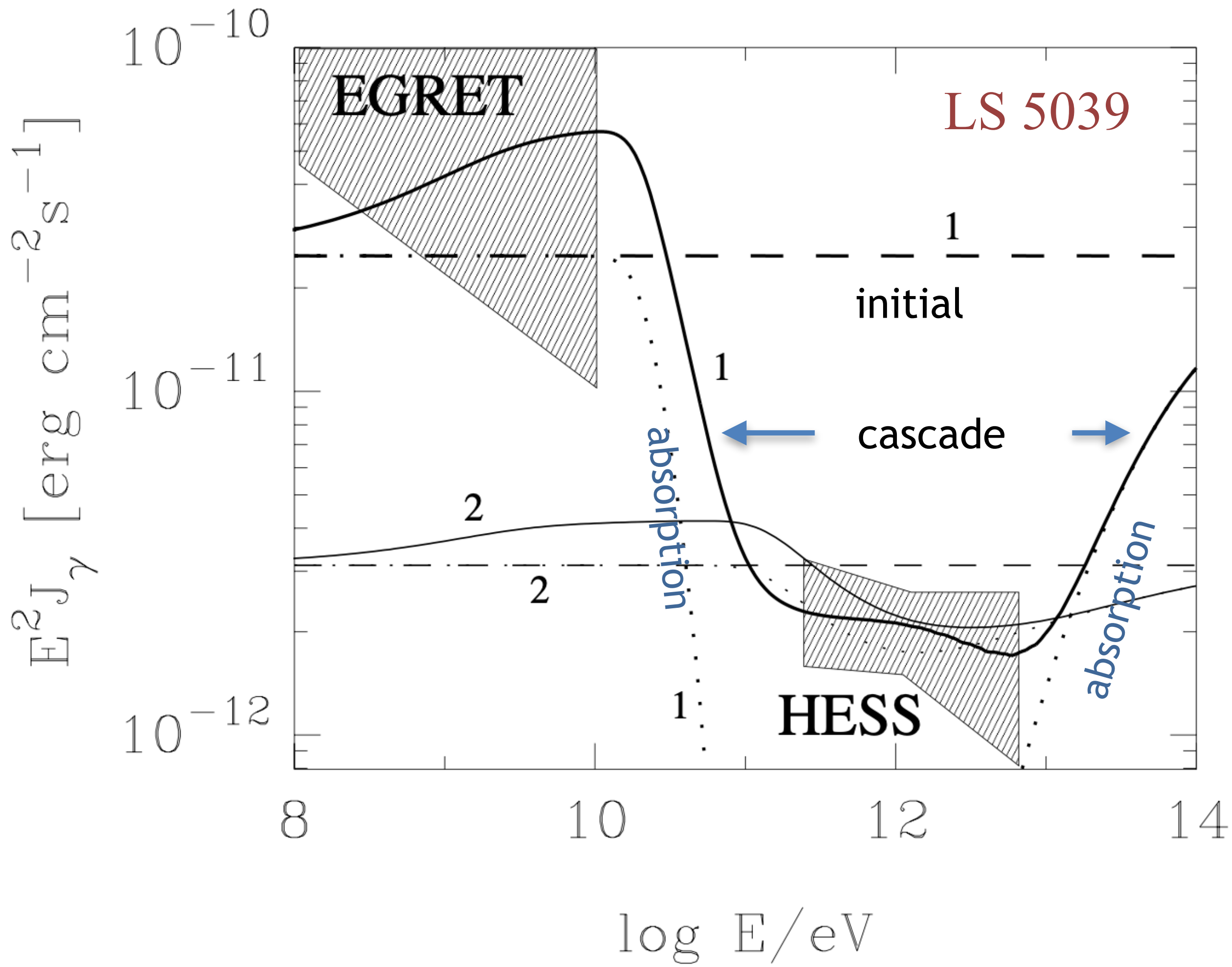
EHE (EeV) gamma-rays interact with
Radio emission:1-10MHz: 1Mpc<d<10Mpc

UHE (PeV) gamma-rays interact effectively
with 2.7K MBR: ~1mm 10kpc <d< 1Mpc

VHE (TeV) gamma-rays interact effectively
with EBL: 0.1-100 μm 100Mpc<d<1Gpc

Universe is (almost) transparent for <10 GeV
gamma-rays, z>3



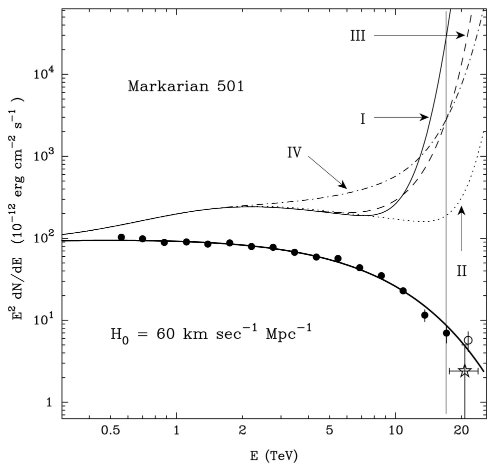


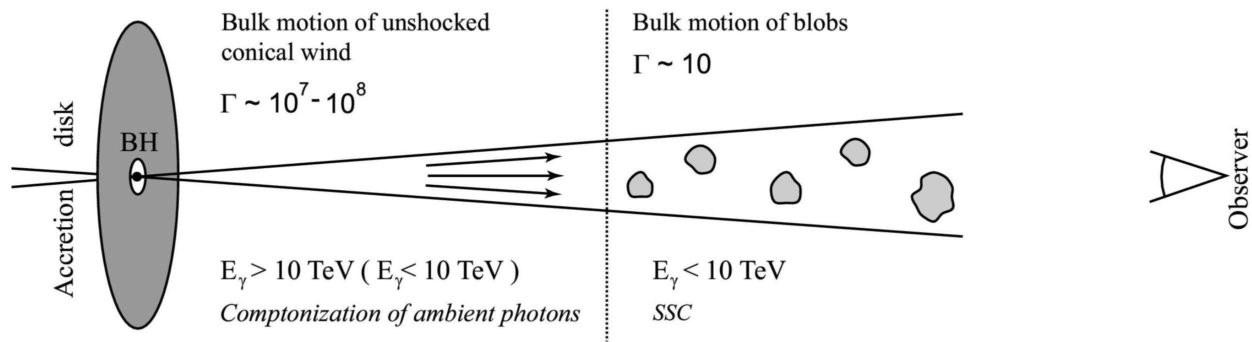
1,2 - different locations of γ-production region

effects of $\gamma\gamma \rightarrow e^+e^-$ in a gamma-ray loud binary system LS 5039

absorption can make *harder* gamma-ray spectrum at highest energies!

unusual “spiky” feature in the gamma-ray spectrum of Mkn 501 ? (after correction for intergalactic absorption)





proposed to explain unusual spectral shapes of TeV emission of blazars… in fact it is not a very-exotic-scenario - it constitutes the basis of paradigm of pulsar winds and PWNe

when $\Gamma\varepsilon > m_e c^2$, $E_\gamma = \Gamma m_e c^2$ (IC in (K-N regime) => direct measurement of the bulk Lorentz factor

IC gamma rays from Cold Ultrarelativistic Outflow?

energy spectra and cooling times

for electron spectrum $\mathrm{d}N_\mathrm{e}/\mathrm{d}E_\mathrm{e} \propto E_\mathrm{e}^{-\Gamma}$

IC spectrum in nonrelativisticalistic (Thompson) limit $a = 4\omega_0\varepsilon_\gamma \ll 1$

$$E_\gamma^{-\frac{\Gamma+1}{2}}$$

$$a = 4\omega_0\varepsilon_\gamma >> 1$$

IC γ-ray spectrum in relativistic (Klein-Nishina) limit

$$E_\gamma^{-(\Gamma+1)}(\ln E + const)$$

energy loss time: $\frac{\mathrm{d}\varepsilon_\mathrm{e}}{\mathrm{d}t} = \frac{4}{3}\sigma_\mathrm{T} c\omega_0 n_\mathrm{ph}\varepsilon_\mathrm{e}^2 \quad \text{at} \quad a \ll 1$

$$\frac{\mathrm{d}\varepsilon_\mathrm{e}}{\mathrm{d}t} = \frac{3}{8}\frac{\sigma_\mathrm{T} c n_\mathrm{ph}}{\omega_0}(\ln 4a - 11/6) \quad \text{at} \quad a \gg 1$$

cooling time: $t_\mathrm{IC} = \frac{\varepsilon_\mathrm{e}}{(\varepsilon_\mathrm{e}/dt)} \propto \varepsilon_\mathrm{e}^{-1} \quad \text{in Thompson regime}$

$$t_\mathrm{IC} \propto \varepsilon_\mathrm{e}/(\mathrm{lnE} + \mathrm{const}) \quad \text{in Klein} - \text{Nishina regime}$$

some interesting features related to Klein-Nishina effect

if IC losses dominate over synchrotron losses

K-N effect makes electron spectrum harder (α => α-1)

but gamma-ray spectrum steeper (α-1+1 -> α)

for IC γ-rays it operates twice in opposite ways => hard γ-ray spectrum

for Synchrotron it works only once => very hard synchrotron spectrum

if synchrotron losses dominate over IC losses

Synch losses make electron spectrum steeper (α => α+1)

K-N effect makes gamma-ray spectrum steeper (α+1+1 -> α+2)

=> *very steep γ-ray spectrum:* $\Gamma = \alpha+2$

=> *standard synchrotron spectrum:* $\Gamma = 1+\alpha/2$

Anisotropic Inverse Compton

energy spectrum of upscattered photons at an angle in respect to the direction of

a beam of monoenergetic photons penetrating through relativistic electron plasma

$$\frac{d^2N(\theta,\omega)}{d\omega\, d\Omega} = \frac{r_0^2}{2\omega_0 E^2}\left[1 + \frac{\omega^2}{2E(E-\omega)} - \frac{\omega}{\omega_0 E(E-\omega)(1-\cos\theta)} + \frac{\omega^2}{2\omega_0^2 E^2 (E-\omega)^2 (1-\cos\theta)^2}\right]$$

$$\equiv \frac{r_0^2}{2\omega_0 E^2}\left[1 + \frac{z^2}{2(1-z)} - \frac{2z}{b_\theta(1-z)} + \frac{2z^2}{b_\theta^2(1-z)^2}\right], \qquad (20)$$

where $b_\theta \equiv 2(1-\cos\theta)\omega_0 E$, $z \equiv \omega/E$, and ω changes in the limits

$$\omega_0 \leqslant \omega \leqslant \frac{b_\theta}{1+b_\theta} E. \qquad (21)$$

can be used in astrophysical scenarios when we deal with anisotropic target photon fields a quite important factor which cannot be ignored

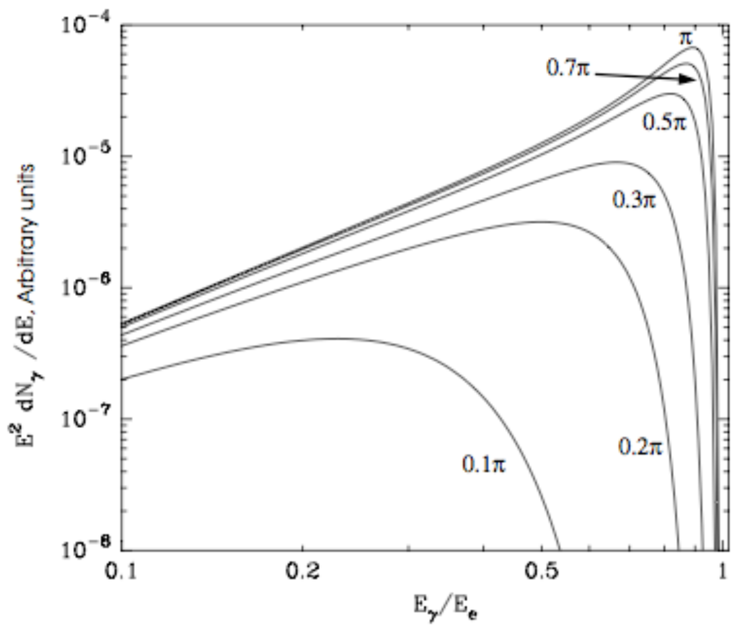


Figure 5. Dependence of the IC energy spectrum on the interaction angle: $\theta_{IC} = 0.1\pi, 0.2\pi, 0.3\pi, 0.5\pi, 0.7\pi, \pi$. It is assumed that monoenergetic electrons ($E_e = 0.1$ TeV) interact with blackbody photons ($T = 3.8 \times 10^4$ K).

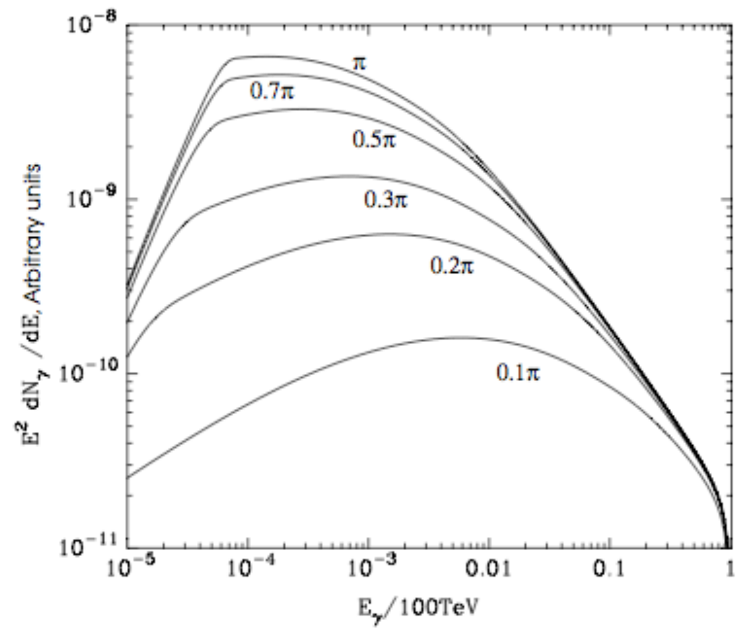
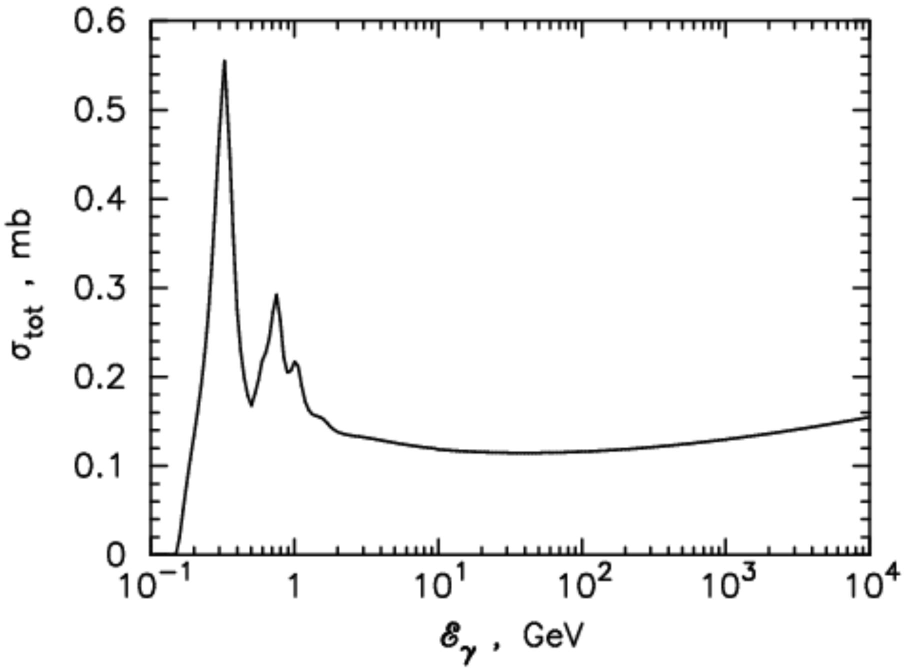


Figure 6. Angular dependence of the IC cross-section. The result of the interaction of a power-law electron distribution with a blackbody distribution of target photons ($T = 3.8 \times 10^4$ K) is shown for the following values of the interaction angle: $\theta_{IC} = 0.1\pi, 0.2\pi, 0.3\pi, 0.5\pi, 0.7\pi, \pi$.

there is a little doubt that this effect plays an important role in binary systems

interactions of protons with radiation

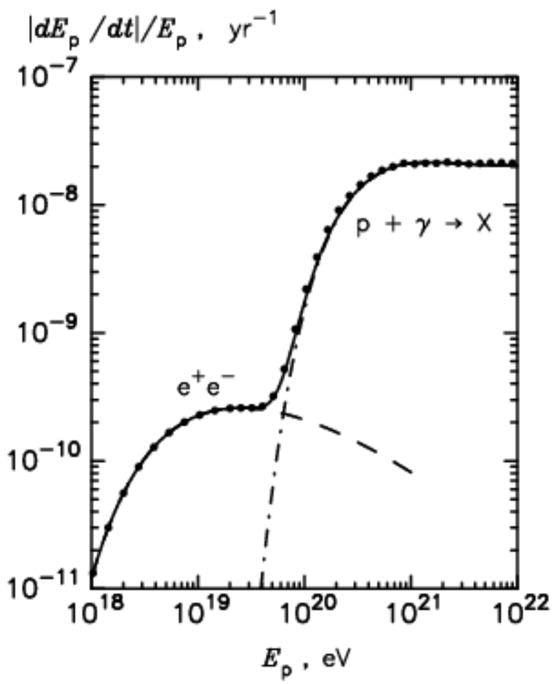


photomeson processes: $p\gamma$ => N +np
$E_{th}=m_\pi c^2\ (1+m_\pi/2m_p)$=145 MeV

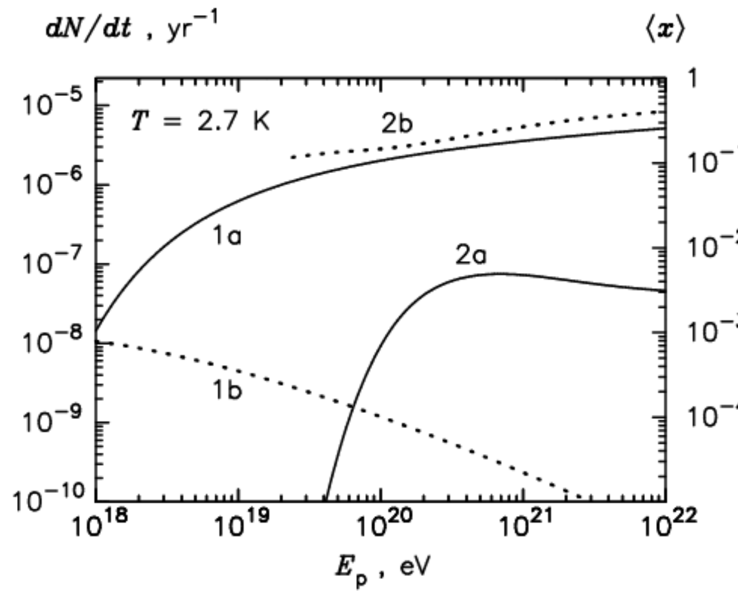
plus

pair production: $p\ \gamma$ => e^+e^-
threshold: $2m_ec^2$=1 MeV

Energy losses of EHE CRs in 2.7 K CMBR due to pair production and photomeson processes

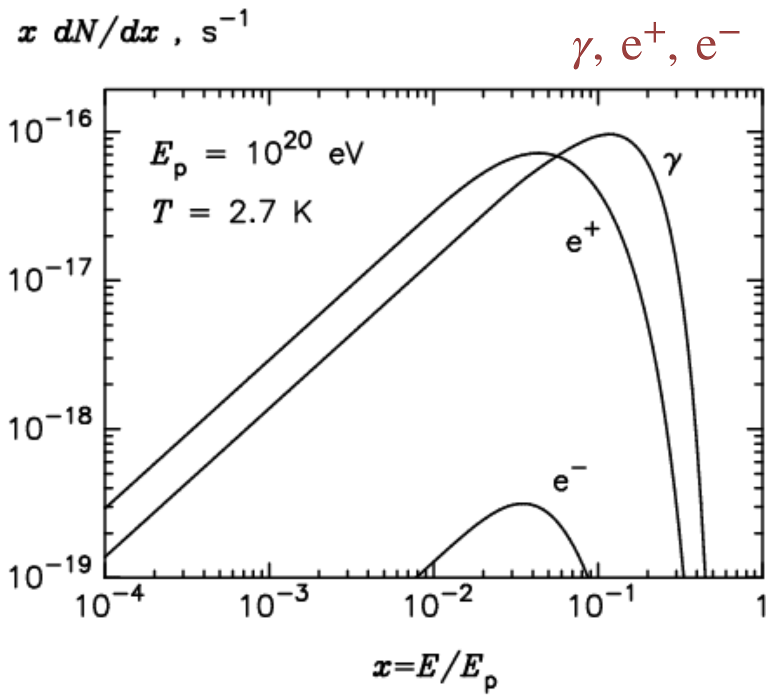


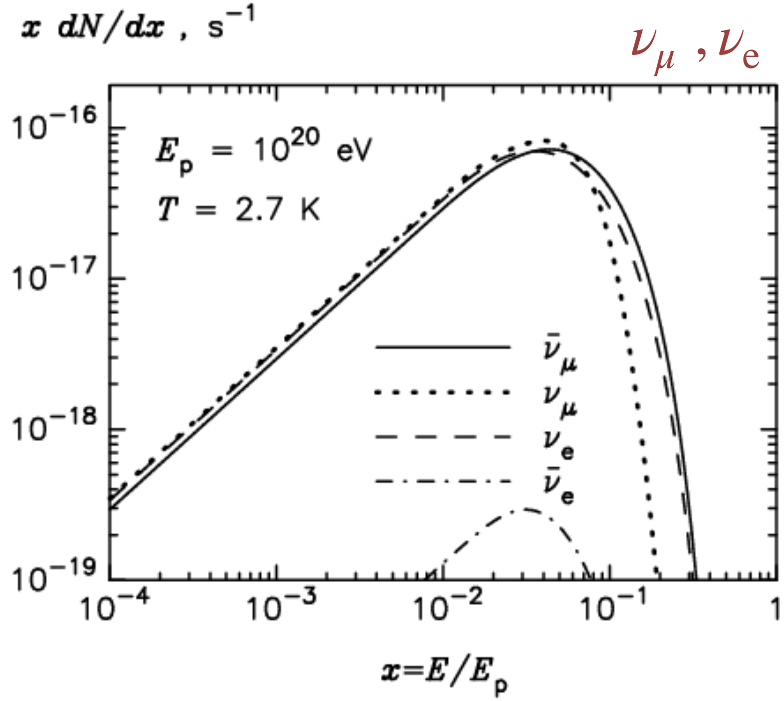
lifetime of protons in IGM



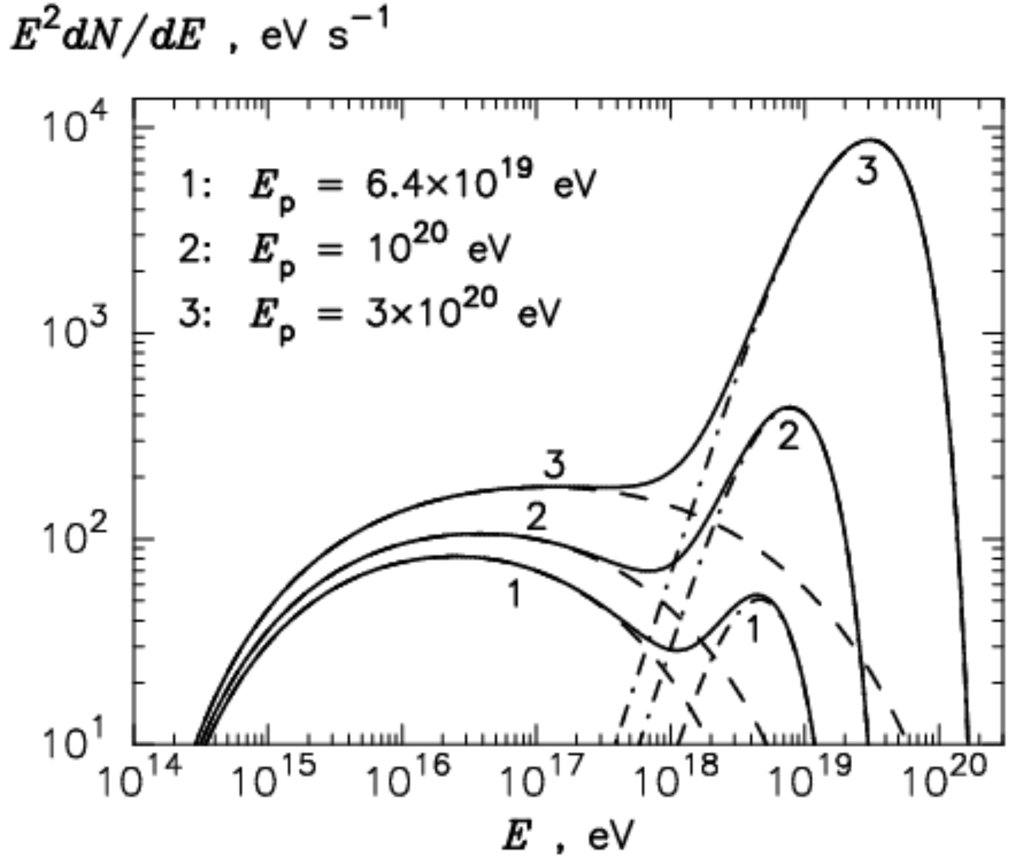
1 - pair production, 2 - photomeson
a - interaction rate, b- inelasticity

distributions of photons and leptons: $E=10^{20}$ eV



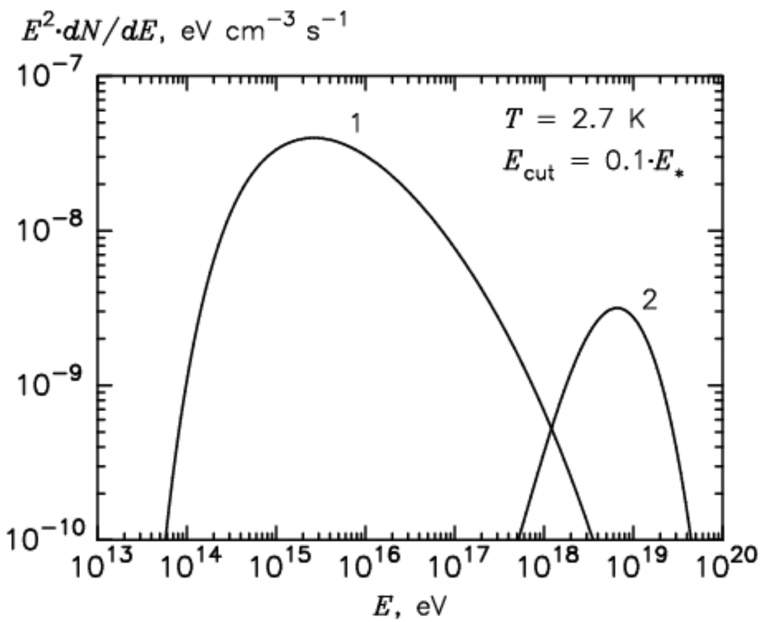


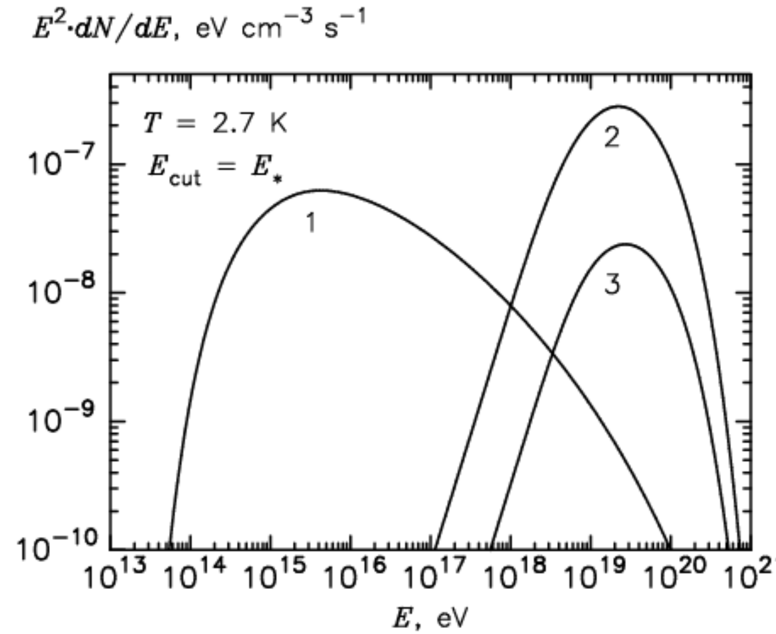
electrons



E^2dN/dE , eV s^{-1}
1: E_p = 6.4×10^{19} eV
2: E_p = 10^{20} eV
3: E_p = 3×10^{20} eV
10^4
10^3
10^2
10^1
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}
E , eV
1
2
3

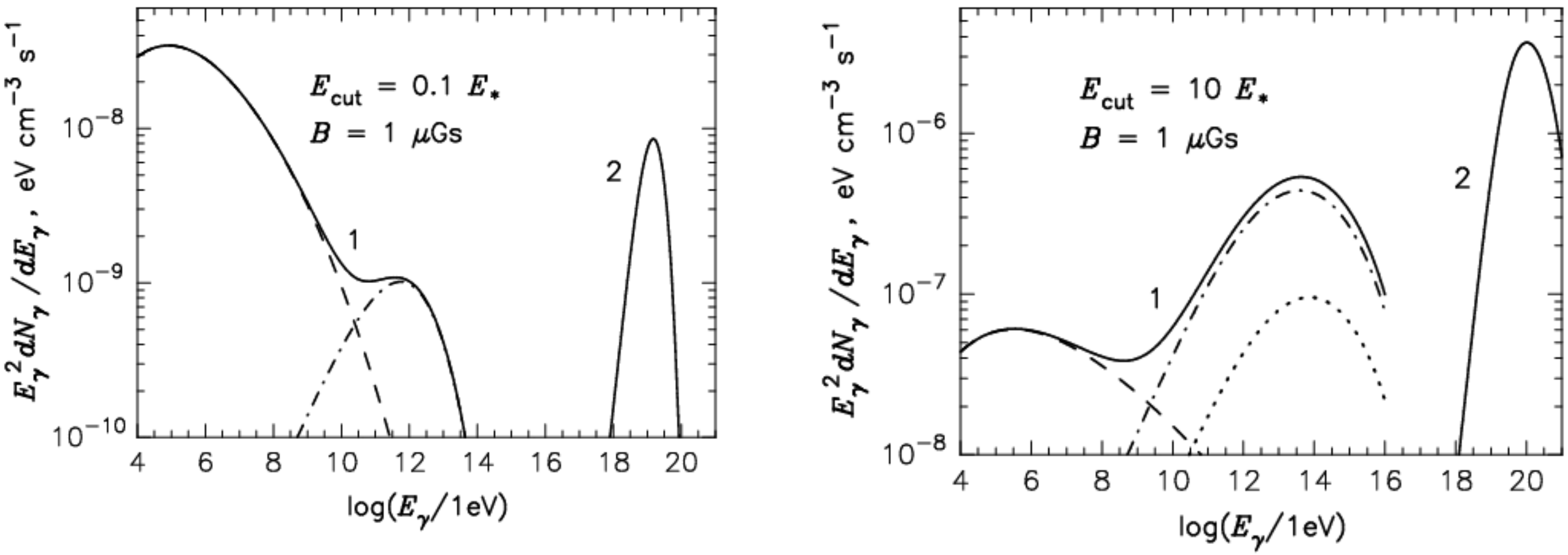
production of electrons in IGM





spectrum of protons: power-law with an exponential cutoff
with power-law index a=2 and cutoff E_{cut}=kE*; E*=3 10^{20} eV

gamma-radiation spectra of secondary electrons



$E^*=3\ 10^{20}$ eV

interactions with magnetic field
photon-photon pair production and Compton scattering

many important results of synchrotron theory are obtained within the framework of classical electrodynamics, i.e.

$$\frac{E_{\rm e}}{m_{\rm e}\ c^2}\frac{B}{B_{\rm cr}} \ll 1 \qquad \text{or} \qquad EB << 10^7 \mathrm{TeV} \cdot \mathrm{Gauss}$$

where $B_{\rm cr} = m_{\rm e}^2 c^3 / e\hbar \approx 4.4 \times 10^{13}$ G - critical magnetic field

Classical regime: energy of synch. photons << energy of electrons

Quantum regime: energy of synch photon is close to electron energy and gamma-rays start effectively interact with B-field and produce electron-positron pairs

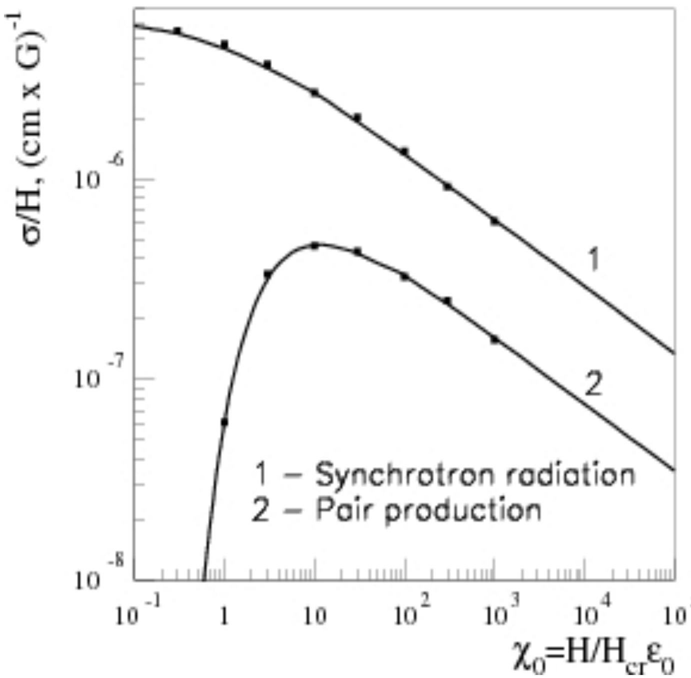
probabilities of both processes depend on a single parameter $\chi_0 = \varepsilon_0 B / B_{\rm cr}$

two are tightly coupled and lead to effective pair-cascade development

synchrotron radiation and pair-production in quantum regime

$$\chi_0 = \varepsilon_0 B / B_{cr}$$

analog of κ_0 and s_0 parameters for IC and $\gamma\gamma$ processes in the photon field



$\chi_0 << 1$ prob. of synch.rad. - constant

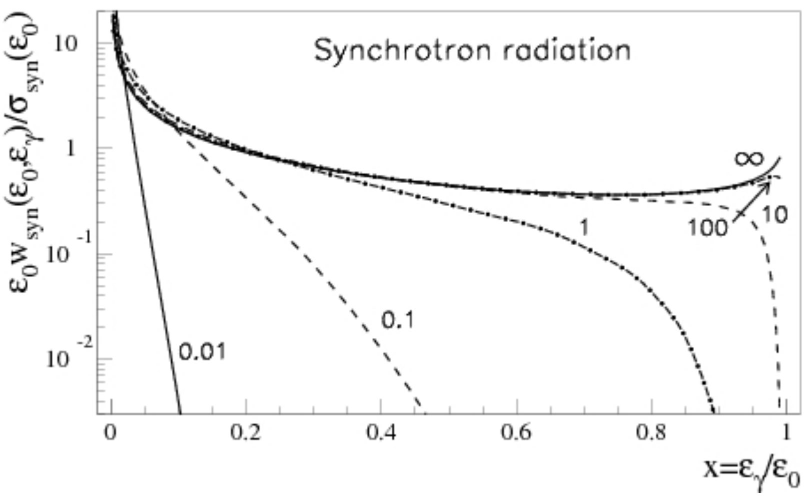
prob of γB: $\exp[-8/(3\chi)]$

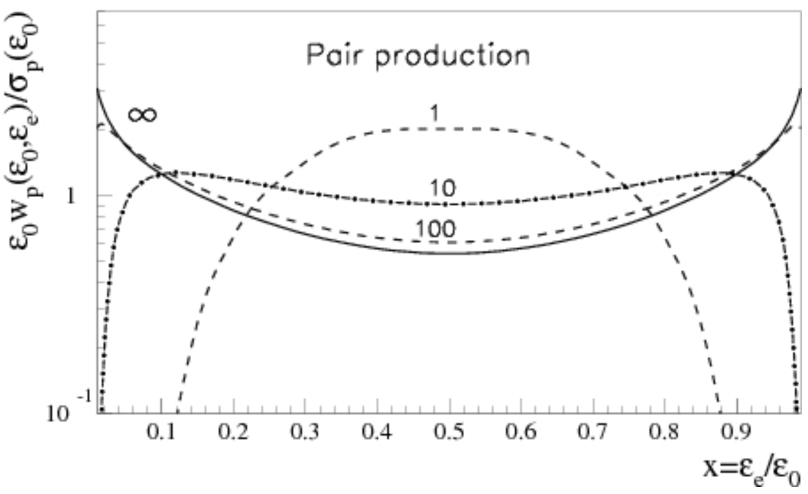
$\chi_0 \approx 10$ prob. of γB: maximum

$\chi_0 >> 1$ prob. of both: $\propto \chi^{-1/3}$

with synch a factor of 3 higher

differential spectra of secondary products produced in magnetic field





at curves are shown values of χ_0 parameter classical synchrotron radiation in the regular and chaotic fields as the most effective mode of realization of Magneto-bremsstrahlung in diverse astrophysical environments from Sun to Galaxy Clusters

it works perfectly in regular, as well as not extremely strong and not extremely turbulent magnetic fields; the efficiency increases with the electron energy $\propto 1/E_e$ and the magnetic field $\propto 1/B^2$

$$t_{cool} \propto \frac{1}{E_e B^2} \propto \frac{1}{B^{3/2} E_{ph}^{1/2}} \qquad E_{ph} \propto B E_e^2$$

the frequency range: from MHz/GHz radio to (almost) gamma-rays

The photon energy $E_{phot} \propto B\ E_e^2$, as long as $E_e \ll 10^{19} (B/1\,G)^{-1} eV$ (classical regime), i.e. formally increases with E_e up to $E_{phot} \sim E_e$ (quantum regime). However, there is more fundamental limit on energy of synchrotron gamma-rays caused by synchrotron losses (!) preventing production of synchrotron photons to GeV energies acceleration rate can be written in the general form:

$$\dot{E} = e\mathscr{E}c = \eta eBc \qquad \eta = \mathscr{E}/B \leq 1$$

$\eta \to 1$ - extreme accelerator determined by ED and ideal MHD

combined with the Synchrotron energy lose rate => E_{max}

synch. peak at $h\nu = \frac{9}{4}\eta^{-1}mc^2/\alpha$ ($\alpha = 1/137$, m - particle mass)

electrons: ≈ 0.15 GeV   protons: ≈ 0.3 TeV

how to extend synchrotron spectrum well beyond 100 MeV ?

- *Radiation in the "curvature mode"*
- *Radiation in extremely turbulent B-field*
- *Synchrotron radiation of heavy charged particles (protons)*
- *Synchrotron radiation of secondary electrons*
- *Acceleration in low B-field, radiation in large B-field*
- *Doppler boosting*

Curvature Radiation

electrons moving along the curved B-field emit emit wither in *synchro-tron* (S) or *curvature* (CR) regimes

in strong B-fields electrons moving along field lines and emit CR

in the case of realization of specific configurations of the E and B fields, the gamma-ray emission of the pulsar magnetospheres can be dominated by the component radiated in the *synchro-curvature* regime.

even for very small pitch- angles, the radiation spectrum can deviates strongly from "ideal CR"

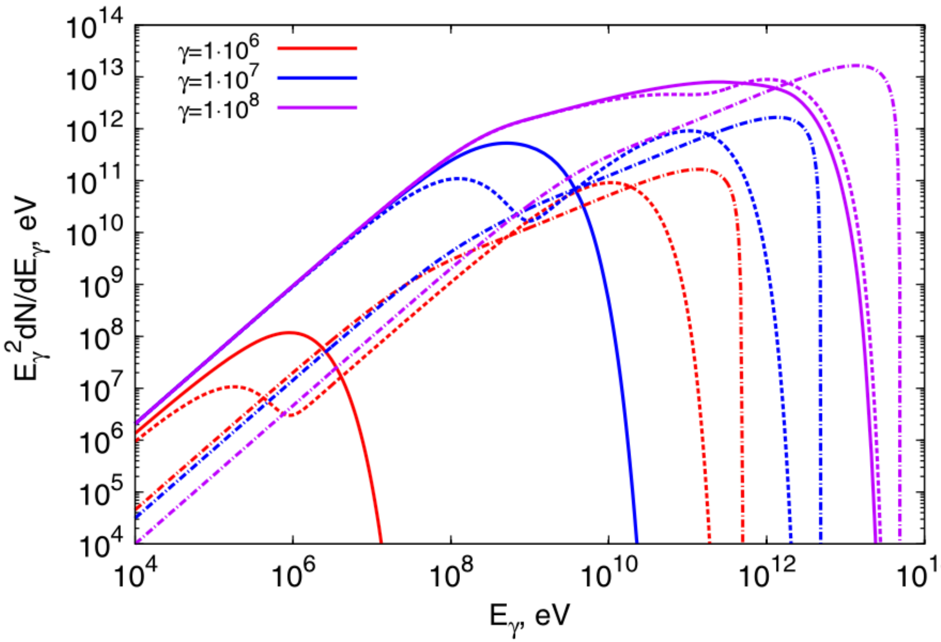
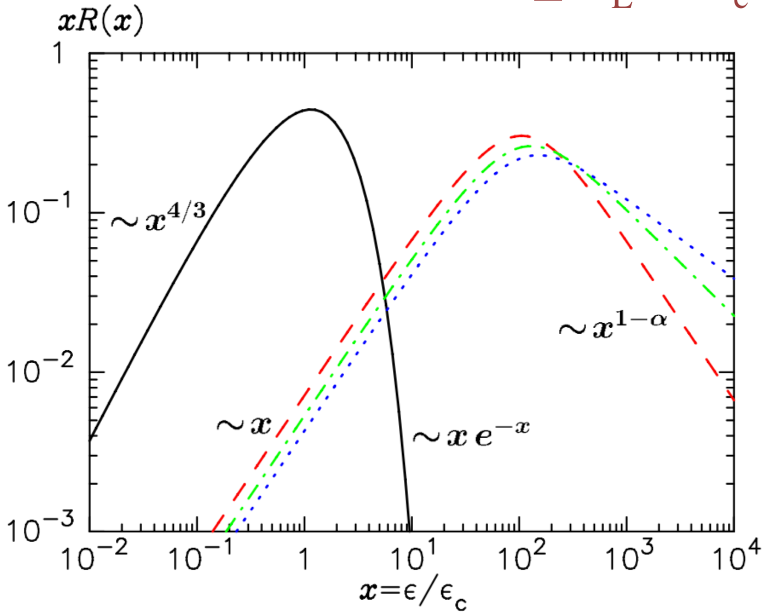


Figure 8. Cumulative (integrated along trajectory) radiation spectra of electrons calculated for the polar cap model in the pulsar magnetosphere. The curves are obtained for different initial Lorentz factors of electrons $\gamma = 10^6$, 10^7, 10^8, and for different initial directions relative to the magnetic field lines: along the magnetic field line (solid lines), and for two pitch angles $1/\gamma_0$ (dashed lines) and $100/\gamma_0$ (dot–dashed lines).

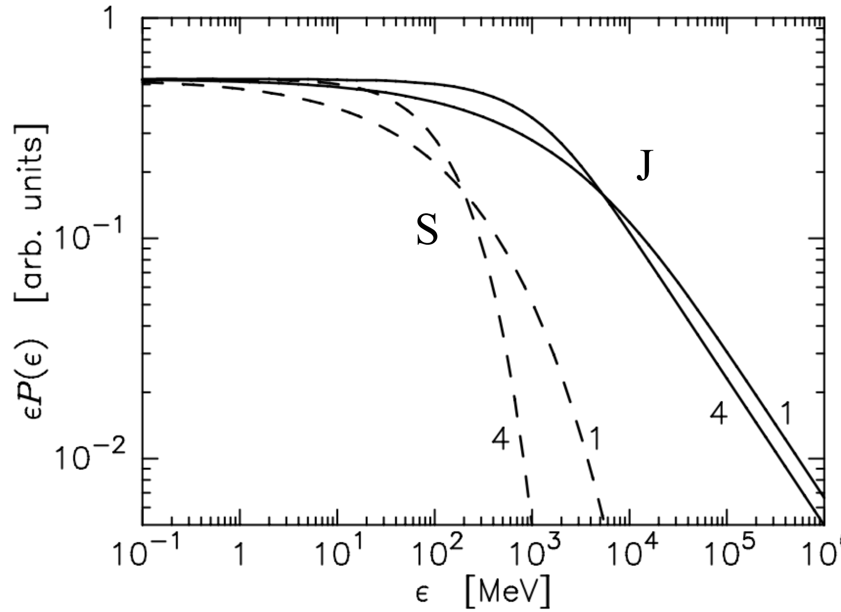
Jitter regime - when the coherence lengh is smaller than Larmor radius

$\lambda \leq R_L = m_c^2/eB \simeq 1.7 \times 10^3\ B_G^{-1}$ cm



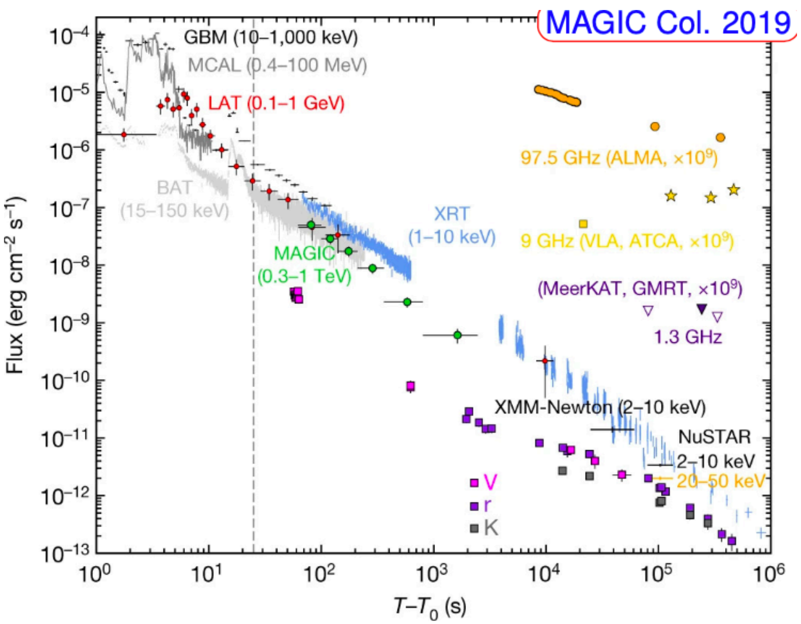
spectrum of monoenergetic electrons

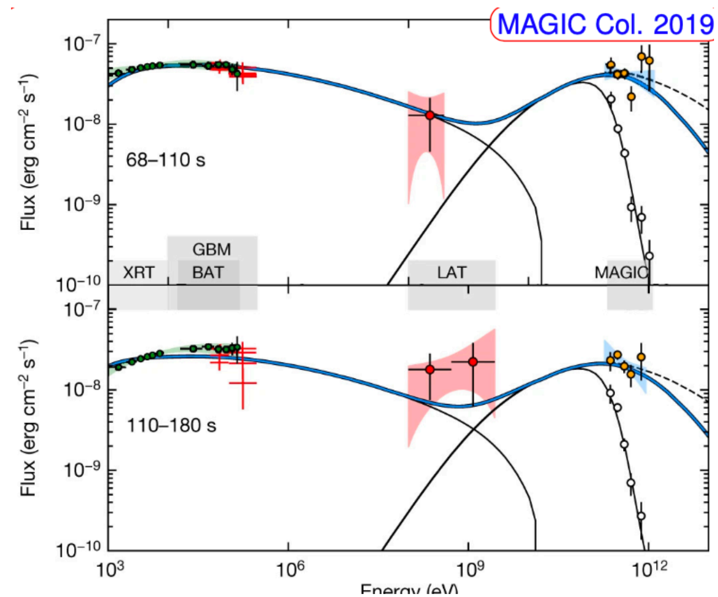
pick is shidted by a factor of R_L/λ

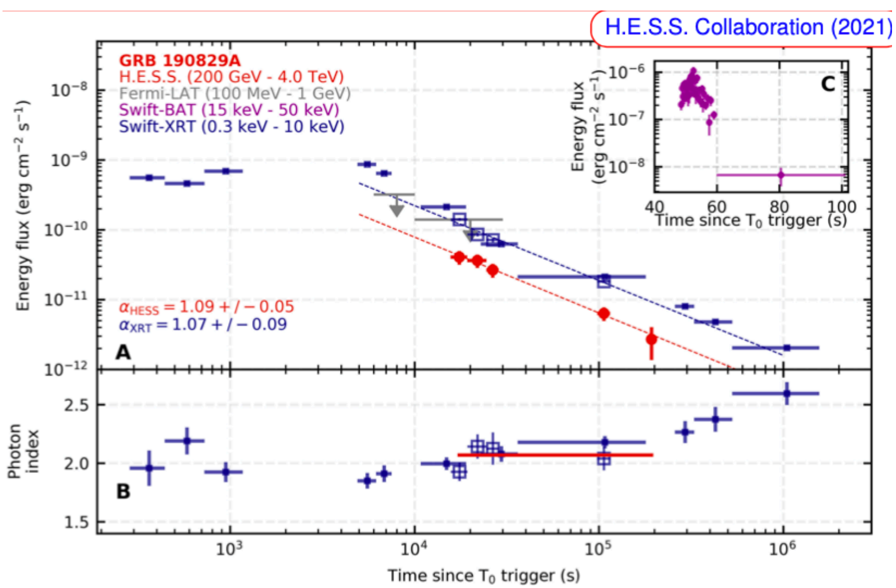


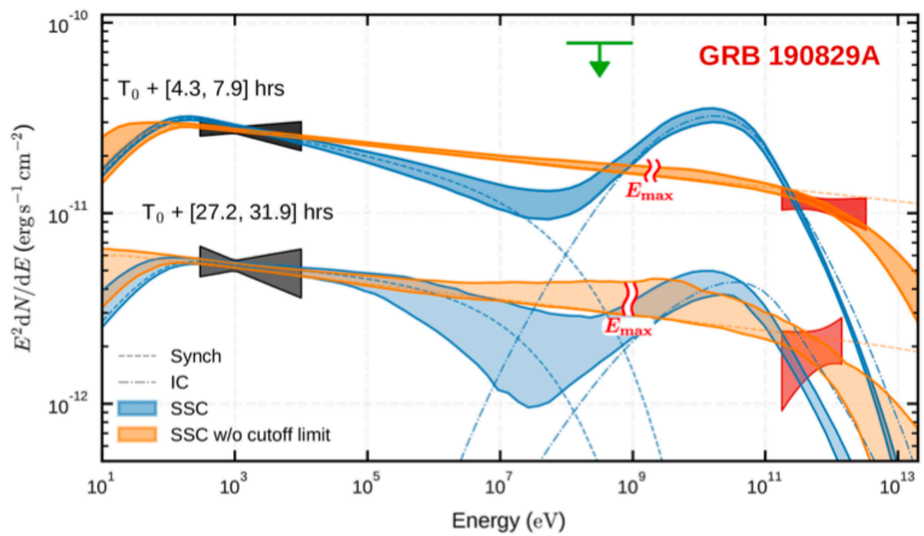
Cutoff in the S spectrum
break in J- spectrum

Detecting GRB afterglows - finally!

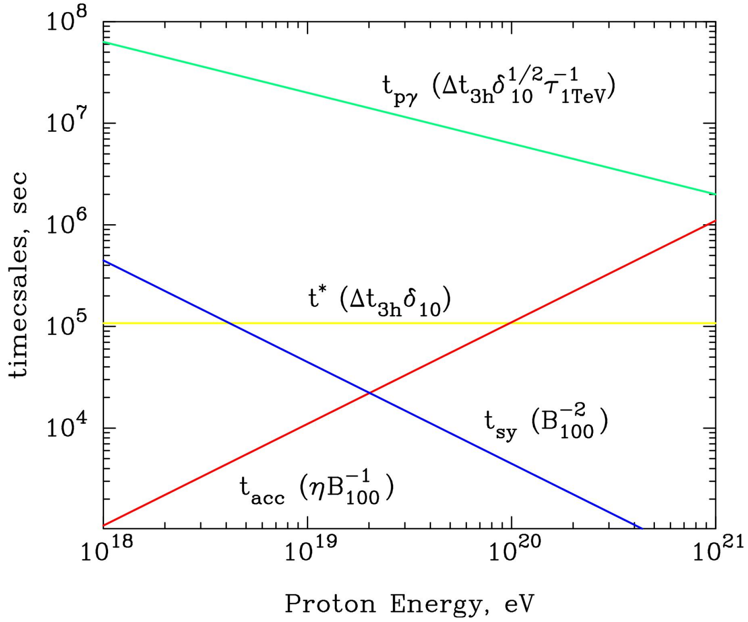




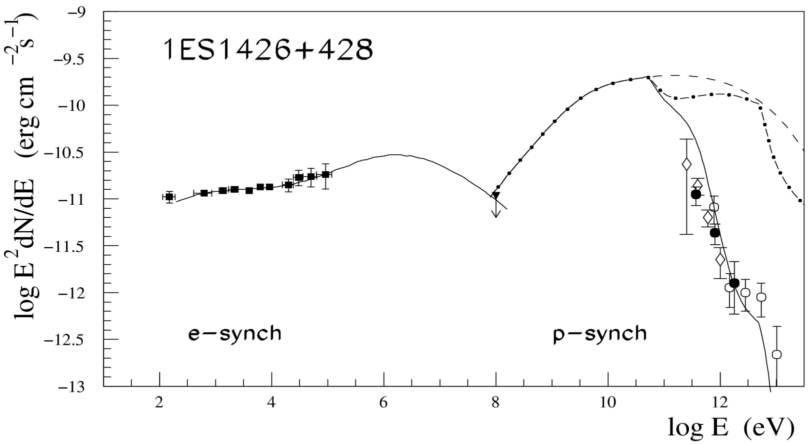




Synchrotron radiation of an extreme proton accelerator



FA 2004



synchrotron radiation of protons: a viable radiation mechanism

E_{cut}=90 (B/100G)(Ep/10^{19} eV)^2 GeV

t_{synch}=4.5x10^4(B/100G)$^{-2}$ (E/10^{19} eV)$^{-1}$ s

t_{acc}=1.1x10^4 (E/10^{19}) (B/100G)$^{-1}$ s

E_{max} =300 η^{-1} δj GeV
requires extreme accelerators: $\eta \sim 1$

cascades

in optically thick for photons environments (L << R) the resulting radiation is formed through the development of E-M cascades supported mainly by

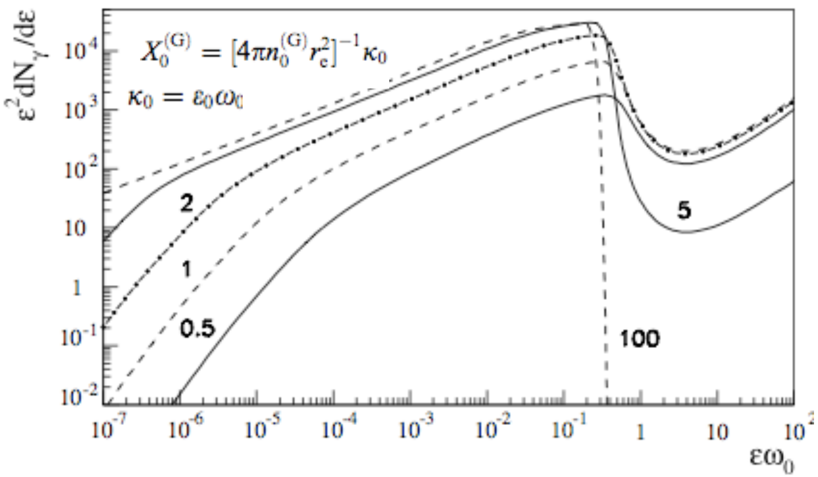
- Bether-Heitler pair production and Bremsstrahlung in Matter
- Photon-photon pair production and Inverse Compton in Photon Fields
- Pair production and Synchrotron Radiation in Magnetic Fields

at certain conditions the cascades can be realized in "pure" forms:

- ✓ *electromagnetic cascades initiated by γ-rays in the Earth's atmosphere (matter),*
- ✓ *in the intergalactic medium initiated by absorption of TeV γ-rays (photon field)*
- ✓ *in pulsar magnetospheres initiated by synchrotron radiation of electrons (B-field)*

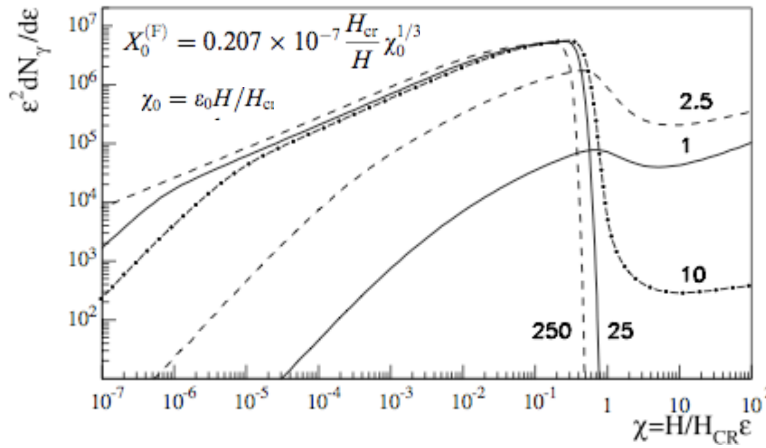
cascades in photon or magnetic fields

Photon-field



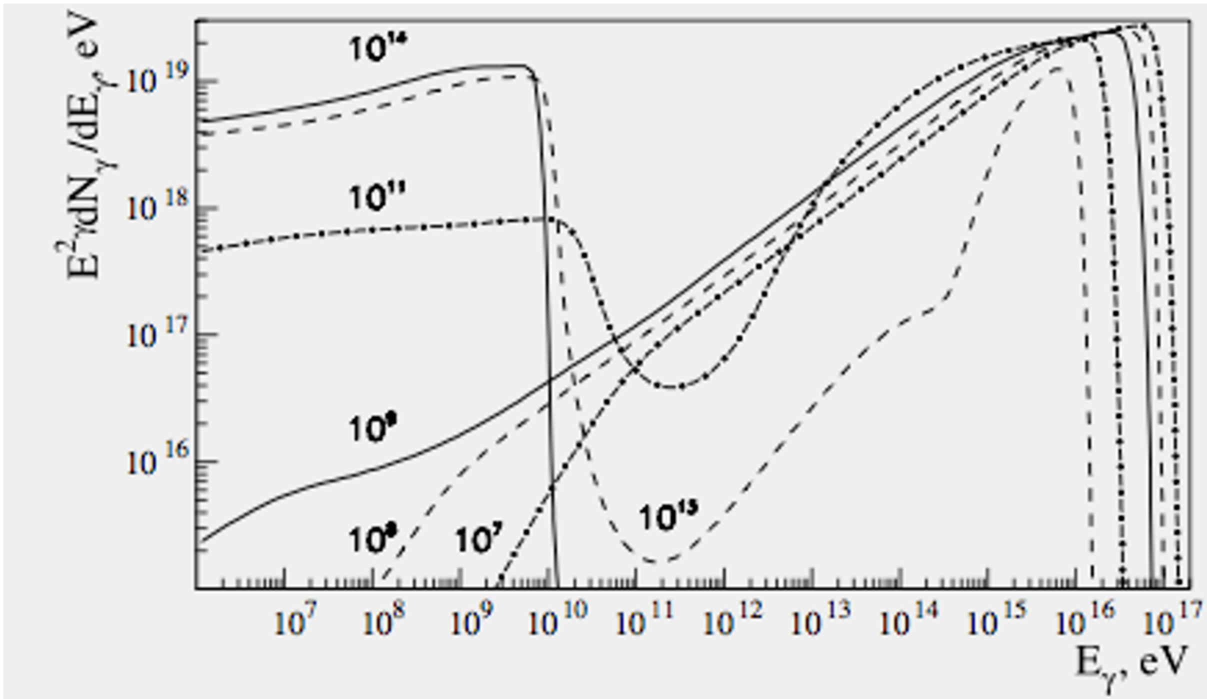
cascade is initiated in BB photon field by a primary gamma-ray with $\kappa_0=10^3$

Magnetic field



cascade is initiated in $B=10^{11}$G by a photon of energy $\varepsilon_0=10^{13}$ eV

Cascade in photon and B-field



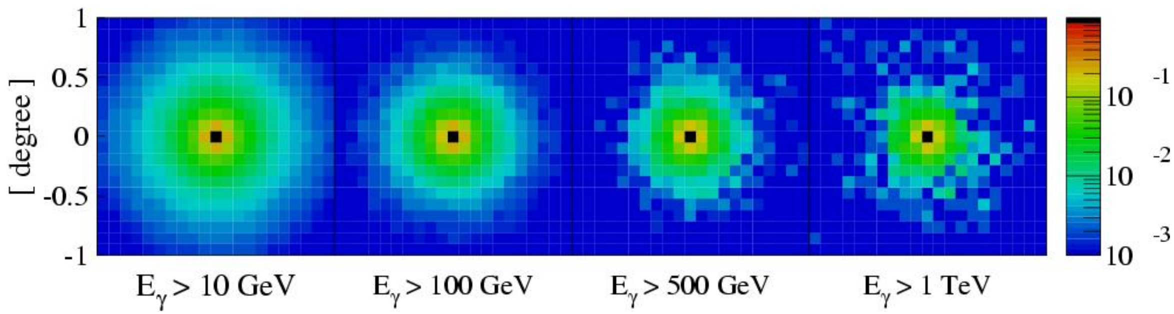
Gamma-ray spectra escaping the source with a size (in cm) indicated at curves. Gamma-rays are formed during development of E-M cascade initiated by a primary gamma-ray photon of energy 10^{20}eV in BB-field of temperature kT=0.3 eV and magnetic field of strength B=100 G.

realization of pair cascades - Giant Pair Halos around AGN

when a gamma-ray is absorbed its energy is not lost !
absorption in EBL leads to E-M cascades suppoorted by

- Inverse Compton scattering on CMBR photons
- photon-photon pair production on EBL photons

if IGM is sufficiently strong, $B > 10^{-11}$ G, the e^+e^- pairs are promptly isotropised =>
formation of extended (relic) structures – Pair Halos
unique cosmological candles with or without the central sources



z=0.129

quick estimates of γ-ray fluxes and spectra

this can be done, in many cases with a surprisingly good accuracy, using cooling times (for energy fluxes)

$$F_\gamma = W_{p(e)}/4\pi d^2 t_{cool}$$

and δ-functional approximation (for energy spectra) using the relation

$$\langle E_\gamma \rangle = f(E_{p(e)})$$

but be careful with δ-functional approximations ...

this may lead to quite wrong results

two examples

often for particle (electron or proton) spectrum is assumed a convenient power-law with exponential cutoff spectrum, in a general form:

$$dN/dE = KE^{-\alpha} \exp[-(E/E_0)^{\beta}]$$

the cutoff region - *more important than any other energy region* - can be derived from the spectrum of radiation, e.g.

- synchrotron radiation: $\varepsilon^{-(\alpha+1)/2} \exp[-(\varepsilon/\varepsilon_0)^{\beta'}]$

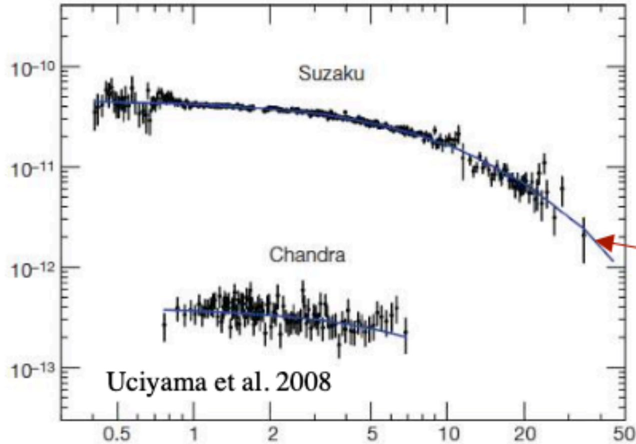
  δ-functional approximation: $\beta' = \beta/2$ ($\varepsilon \sim E^2$), precise $\beta' = \beta/(\beta+2)$

  $\beta=1 \Rightarrow \beta'=1/3$ but not 1/2; $\beta=2 \Rightarrow \beta'=1/2$ but not 1/4

- p+p -> π^0 -> γ: $\varepsilon^{-\alpha'} \exp[-(\varepsilon/\varepsilon_0)^{\beta'}]$

  δ-functional approximation: $\alpha' = \alpha$, $\beta' = \beta$ ($\varepsilon \sim 1/10E$)

  precise $\alpha' \approx \alpha + 0.1 \quad \beta' \sim 0.5$



energy spectrum of synchrotron radiation of electrons in the framework of DSA (Zirakashvili&FA 07)

$$J_\nu \propto \nu^{-1}[1 + 0.46(\nu/\nu_0)^{0.6}]^{11/4.8} \exp[-(\nu/\nu_0)^{1/2}]$$

$$h\nu_0 \approx 1(v/3000\mathrm{km/s})^2\eta^{-1}\ \mathrm{keV}$$

$h\nu_0$=0.55 keV

strong support for acceleration in Bohm diffusion regime ($\eta \sim 1$) - from postion of synchrotron cutoff given that the shock speed v < 4000 km/s (Chandra)

an example: diffusive shock acceleration of electrons

in the Bohm diffusion regime; losses dominated by synchrotron radiation

$$N(E) \propto E^{-2}[1 + 0.523(E/E_0)^{9/4}]^2 \exp[-(E/E_0)^2] \quad (*)$$

E_0 *almost coincides with the value derived from* $t_{acc} = t_{synch}$

the spectrum of synchrotron radiation at the shock front

$$J_\nu \propto \nu^{-1}[1 + 0.46(\nu/\nu_0)^{0.6}]^{11/4.8} \exp[-(\nu/\nu_0)^{1/2}]$$

$$h\nu_0 = 1(v/3000\ \mathrm{km/s})^2\eta^{-1}\ \mathrm{keV}$$

1. electron spectrum derived from Suzaku data
2. DSA prediction
3. "standard E^{-3} exp($-E/E_0$) type elec. spectrum

two errors combined - (i) exponential cutoff in the spectrum of accelerated electrons and (ii) δ-functional approximation for synch. radiation compensate each other and give (accidentally!) relatively correct behavior in the cutoff region

few examples of efficient/inefficient
γ-ray emitters related to cosmic rays

inefficient!

Nonthermal X-ray Bremsstrahlung

at first glance quite attractive (*"why should I invoke multi-TeV electrons to produce X-rays when can I use keV electrons to produce keV X photons?"*) in fact only less than 10^{-5} fraction of the kinetic energy of electrons (protons) is released in X-rays; 99.99…% goes to the ionization and heating of the gas

$$L_e > 10^5 L_X = 10^{37} (f_X/10^{-12} \text{ erg/s}) (d/1\text{kpc})^2 \text{ erg/s}$$

the same is true for <u>gamma-ray line emission due to excitation of nuclei</u> by sub-relativistic protons - both mechanisms "work" during Solar flares, otherwise it typically leads to unreasonably high requirements for production rate of sub-relativistic electrons - this makes the extremely interesting issues like detection of gamma-ray lines, in particular from ISM, SNRs, GMCs, etc (information about the sub-relativistic CRs !) observationally very difficult

$pp \to \pi^0 \to 2\gamma$

not very efficient

no competing dissipation mechanisms - in "calorimetric scenarios": $L_\gamma \sim L_p/3$
but the process itself is not very fast/relatively slow: $t_\pi \sim 10^{15}\,(n/1\mathrm{cm}^{-3})^{-1}$ s
usually the source age or particle escape is a big issue !

SNRs: typical density: $n \sim 1\mathrm{cm}^{-3}$, magnetic field $B \sim 100\mu G$, size $R \sim 3$ pc assuming Bohm diffusion, $D(E)=r_L c/3=10^{25}(E_p/10\mathrm{TeV})^{-1}\ \mathrm{cm}^2/\mathrm{s}$, escape time of protons which produce 1 TeV gamma-rays: $t_{esc} \sim R^2/D \sim 10^{13}$ s $\sim 0.01 t_\pi$

Galaxies - $n \sim 0.1 - 1\,\mathrm{cm}^{-3} => t_{pp\to\pi^o} \sim 10^{7-8}$ yr;
confinement time $10^5 - 10^7$ yr => efficiency 0.1-100 %

Galaxy Clusters: densities $n \sim 10^{-3}$ s, size R>1Mpc - full confinement!
$t_\pi < 10^{18}\,(n/1\mathrm{cm}^{-3})^{-1}$ s - comparable to the age (Hubble time) !

γBinaries: protons accelerated by the compact object and interacting with the dense stellar disk of companion: $n \sim 10^{13}\ \mathrm{cm}^{-3}$; the cooling time could be shorter than escape time => potentially effective production of gamma-rays and νs

higher efficiencies at MeV/GeV energies because of problem of confinement

Synchrotron radiation

very efficient

especially in extreme particle accelerators where acceleration proceeds at the maximum (theoretically possible) rate and the further acceleration is limited by synchrotron losses

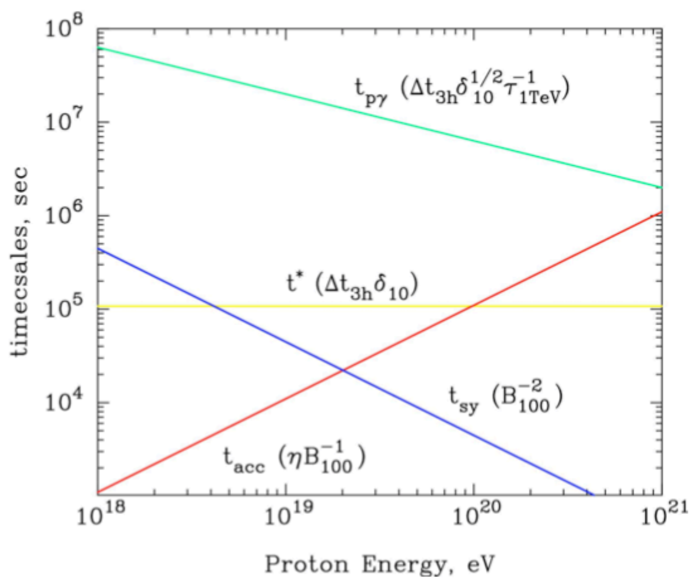
$$t_{\rm acc} = \frac{R_L}{c}\eta^{-1}$$ => self regulated cutoff

$$h\nu_{\rm cut} = \frac{9}{4}\alpha_f^{-1} mc^2 \eta :$$

$\simeq 300\,\mathrm{GeV}$ proton synchrotron

$\simeq 150\,\mathrm{MeV}$ electron synchrotron

proton-synchrotron is effective in compact objects with large B-fields (when $t_{coo} < R/c$)



$t_{synch}=4.5\times10^4 (B/100G)^{-2} (E/10^{19}\,eV)^{-1}$ s

$t_{acc}=1.1\times10^4 (E/10^{19}) (B/100G)^{-1}$ s

$E_{max} \sim B^{-1/2}$, but $h\nu_{cut}$ - independent of B

$t(h\nu_{cut})=2.4\times10^4 (B/100G)^{-3/2} \eta^{1/2}$ s $< R/c$

$B > 100 (R/10^{15}cm)^{-2/3} \eta^{1/3}$ G

IC: $e\gamma \rightarrow e+\gamma'$

very efficient

- ✓ compact objects - binaries, AGN… -
  very effective with some exceptions

- ✓ PWNe with very small B-field: $L_{IC} = (w_{MBR}/w_B)\dot{W}_e = (B/3\mu G)^{-2}\dot{W}_e \sim \dot{W}_e$
  if B <3mG; thanks to very effective (relativistic shock?) acceleration
  electrons still can be accelerated to 100 TeV or beyond

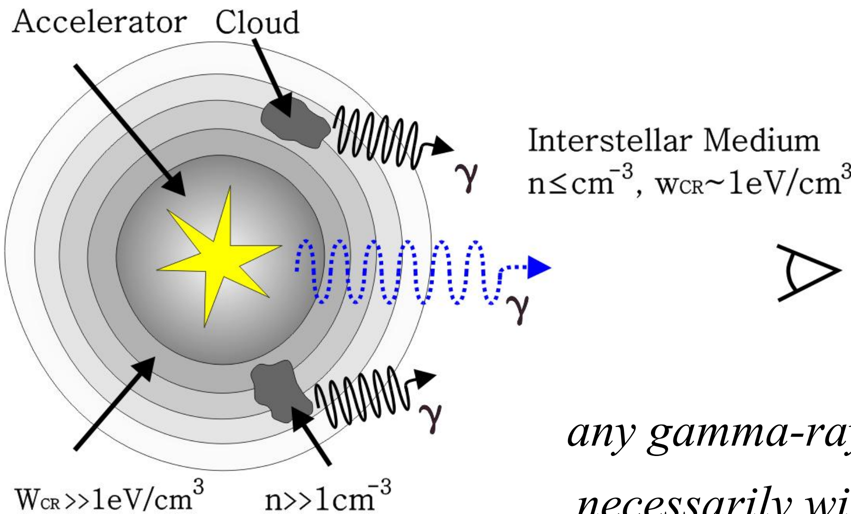
- ✓ Clusters of Galaxies - despite small B-field (~ 1μG) and limited shock speed (~ 2000 km/s), thanks to the large size and age of these cosmological structures, protons can be accelerated to 1018-1019 eV, produce secondary (Bethe-Heilter) pairs at interactions with 2.7K CMBR, and the secondary electrons can produce effective IC gamma-rays upscattering 2.7K CMBR

- ✓ 1 many other realisations and … tricks related e.g. to Klein-Nishina scattering regime

often is accompanied with photon-photon pair-production

gamma-ray production: accelerator+target

existence of a powerful particle accelerator by itself is not sufficient for γ-radiation; an additional component – a dense target - is required



➢ target - *matter, radiation, magnetic field*

any gamma-ray emitter coincides with the target, but not necessarily with the "primary" source/particle-accelerator

extended sources of hadronic gamma-rays: $F_\gamma(r) \propto N_{CR}(r)\, n_{gas}(r)$

✓ gamma-ray distribution correlates with gas distribution only for homegenous CR distribution

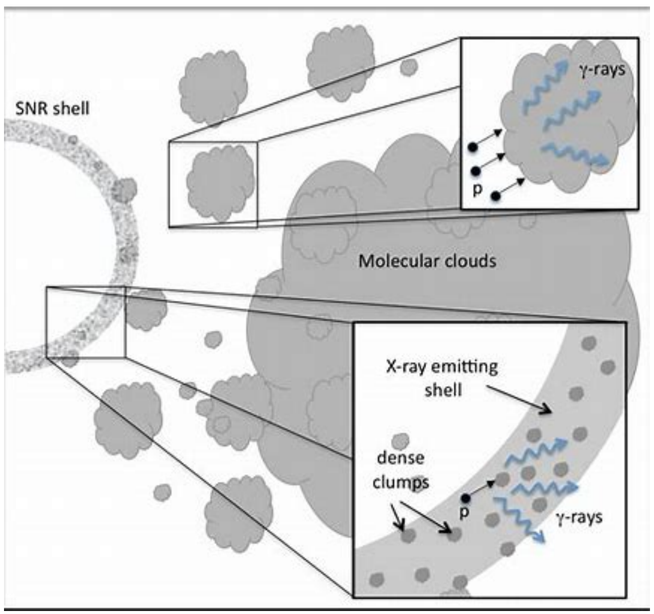
✓ because of CR propagation of CRs, we should expect energy dependent γ-ray morphology

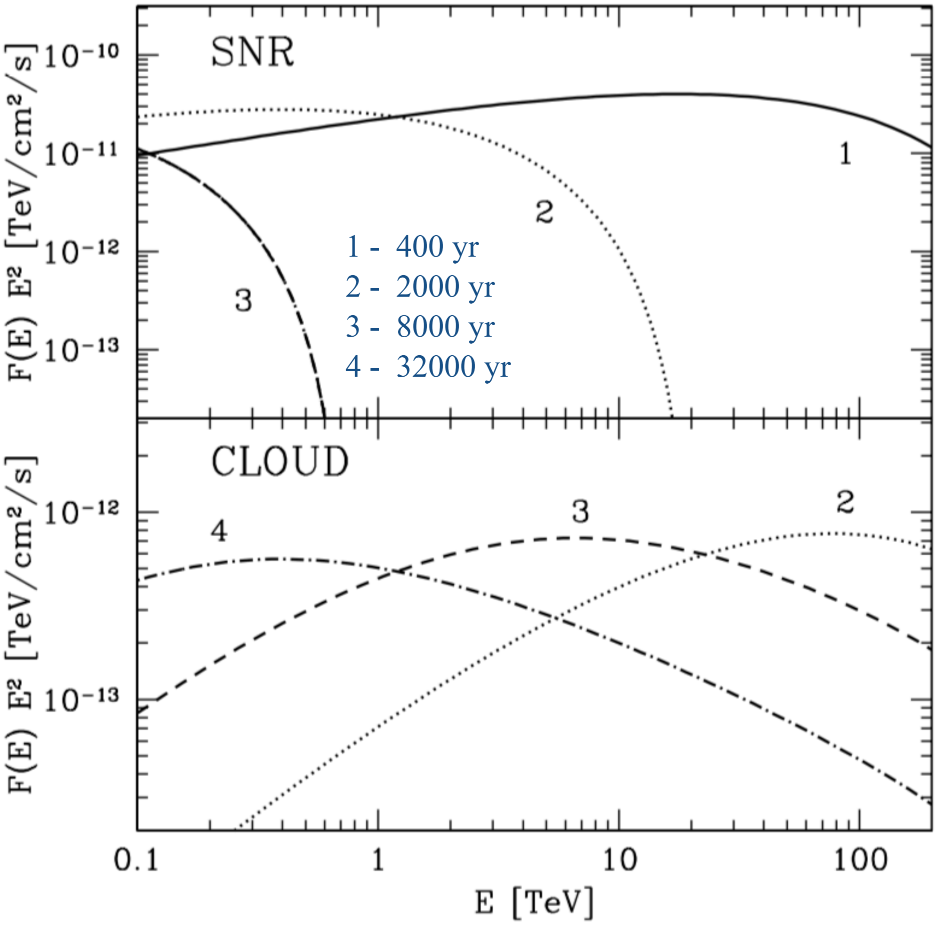
✓ CR total energy $W_{CR} \approx L_\gamma \times t_{pp\rightarrow\pi^0}$ is relevant only for regions from which γ-rays are detected

one accelerator - *two* gamma-ray sources

middle-aged SNR - former particle accelerator and emitter of GeV γ-rays

nearby gas Cloud - GeV to PeV γ-ray emitter





SNR: $W=10^{51}$ erg $n= 1$ cm^{-3}
$f(p) \sim p^{-4}$; $p_{max}=5$ PeV;
$p_{max} \sim t^{-2.4}$

Cloud: $R=100$ pc, $M=10^4 M_o$
$D(E)=3\times10^{29}(E/1\mathrm{PeV})^{0.5}$ cm^2/s

some specifics of cosmic γ-ray production

gamma-ray production efficiency

many reported TeV gamma-ray sources require not only extreme particle accelerators but also effective production of gamma-rays

effective gamma-ray production?

cooling time of the given gamma-ray production process is shorter than

(1) timescales of radiative and non-radiative (e.g. adiabatic) losses
(2) intrinsic dynamical (source age, acceleration time, particle escape time)

Note: high efficiency is an important but not sufficient/decisive condition for a gamma-ray sources to be detected. The detectability depends also on

- ✓ power and distance to the source ($\sim W/d^2$)
- ✓ beaming factor, e.g. Doppler boosting ($\sim \delta^4$)
- ✓ Sensitivity of the instrument in the given energy domian

$$W_{cr} = L_\gamma t_{rad} \qquad \dot{W}_{cr} = \kappa L_\gamma \qquad \kappa = t_{rad}/t_{dis} \;;\; \kappa \geq 1$$

$\kappa \sim 1$ - calorimeter!

be careful with the interpretation of W_{cr} and $\dot{W}_{cr}$: we could miss γ-ray emission from extended emission regions because of the reduced brightness where κ could be different - typically, much smaller

Other astronomical messengers

other astronomical messengers?

astronomical messengers should be neutral & stable:

photons and neutrinos satisfy fully to these conditions

partly also ultra-high energy neutrons and protons …

neutrons: $d < (E_n/m_n c^2)\, c\, \tau_0 \;\Rightarrow\; E_n > 10^{17}(d/1\text{ kpc})$ eV
galactic astronomy with $E > 10^{17}$ eV neutrons

protons: $\phi \sim 1^\circ$ if $E > 10^{20}$ for IGMF $B \leq 10^{-12}$ G
extragalactic astronomy with $E > 10^{20}$ eV protons

Potential TeV neutrino sources

TeV/PeV gamma-ray sources as potential TeV neutrino sources?

yes, if γ-rays of hadronic (*pp* or *p*γ) origin

Detectable (by km^3 class) neutrino detectors ?

yes, if TeV γ-ray flux exceeds 10^{-11} ph/cm^2 s (~1 Crab)

or weaker sources if γ-rays are severely absorbed

e.g. in binary systems like LS 5039, in AGN, GRBs, in IGM

TeV, PeV - gamma rays and neutrinos: carriers of information about hadronic colliders, but

TeV-to-PeV γ-rays: effectively produced/detected, but not easy toidentify the origin of primary particles “hadronic or leptonic?”

PeV/EeV γ-rays: (i) difficult to detect (limited detection areas)
(ii) fragile (absorption in radiation and B-fields)

TeV/PeV/EeV neutrinos: difficult to detect

alternatives? - hard X-rays of secondary electrons?

hard X-rays - “hadronic” messengers?

the idea:

synchrotron radiation of secondary multi-100 TeV electrons produced at interactions of protons with ambient gas or radiation fields

- (1) p p (γ) => π, K, Λ, (2) π, K, Λ => γ, ν, e, μ (3) e B => X
- (1) p γ => e+ e- (2) e B => X

why hard X-rays/low energy gamma-rays?

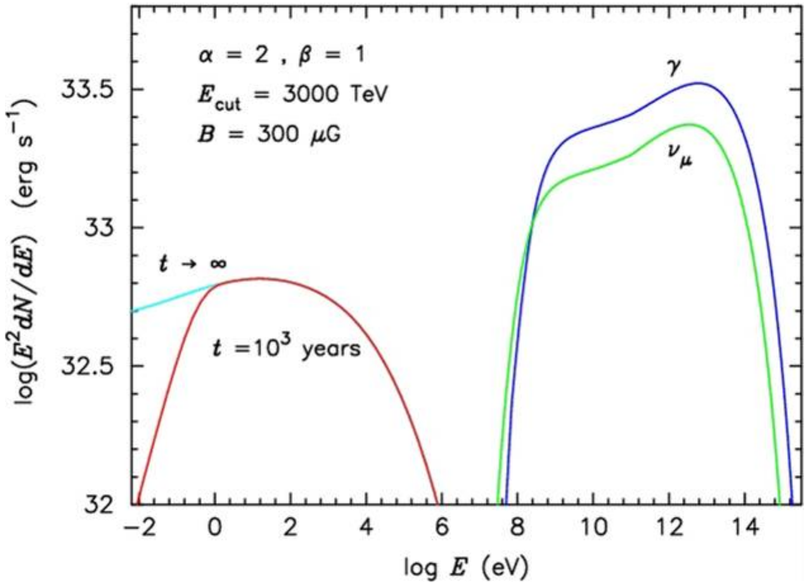
- ✓ radiation often peaks in the hard X-ray band
- ✓ not many competing production mechanisms
- ✓ no absorption in radiation and magnetic fields
- ✓ good sensitivity/good spectrometry/good morphology

secondary electrons from pp interactions

three channels of information
about cosmic PeVatrons:

10-1000 TeV gamma-rays
10-1000 TeV neutrinos

10 -100 keV hard X-rays

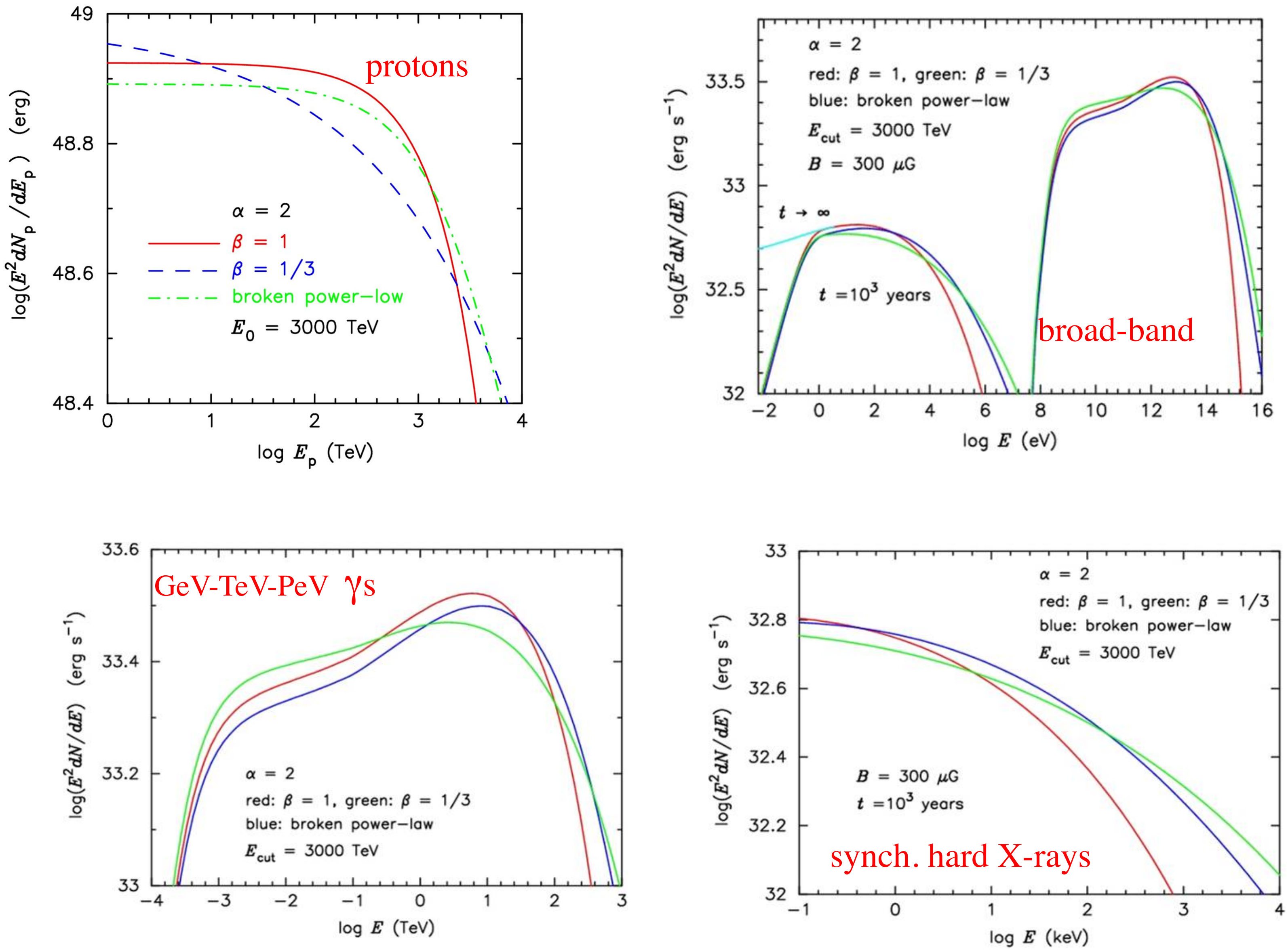


➢ γ-rays: difficult, but possible - LHAASO has detectd tens PeVatron candidates

➢ neutrinos: marginally detectable by IceCube, Km3NeT - don't expect spectrometry, morphology; uniqueness - unambiguous signatute!

➢ "prompt" synchrotron X-rays: smooth spectrum
a very promising channel !

$\sim \varepsilon^{-(\alpha/2+1)} \exp[-(\varepsilon/\varepsilon_0)^{1/5}]$



broad-band emision initiated by pp interactiosn : Wp=10^{50} erg, n=1cm^{-3}

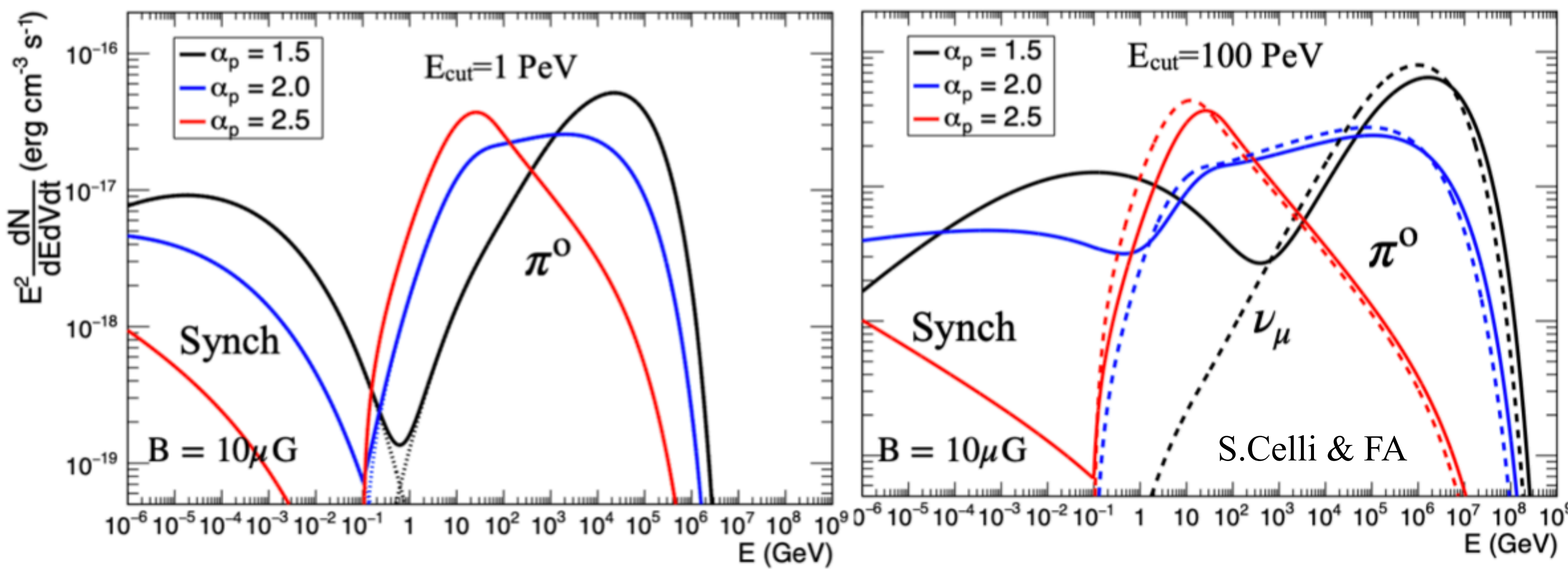
searching for super-PeVatrons with secondary electrons?

synchrotron radiation of secondary electrons: $pp \to \pi^{\pm} \to e^{\pm} + B \to \gamma$

$\epsilon \simeq 20(B/100\mu\mathrm{G})(\mathrm{E}/100\,\mathrm{TeV})^2\,\mathrm{keV}$ - characteristic energy of the synch. photon

$t_{\mathrm{synch}} \approx 15(B/100\mu\mathrm{G})^{-3/2}(\epsilon/10\mathrm{keV})^{-1/2}\,\mathrm{yr}$ - cooling time of electrons

synchrotron radiation almost "prompt" - counterparts of gamma-rays and neutrinos!



normalisation: $\mathrm{n} = 1\,\mathrm{cm}^{-3}$; $\mathrm{w_p}(\geq 100\,\mathrm{GeV}) = 1\,\mathrm{erg/cm^{-}3}$

$\mathrm{F}(10\,\mathrm{keV})/\mathrm{F}(100\,\mathrm{TeV}) \sim 0.1 - 1$; strongest LHAASO sources $\mathrm{F}(100\,\mathrm{TeV}) \approx 10^{-12}\,\mathrm{erg/cm^2 s}$

Seconondairy X-rays and gamma-rays can greatly help to localize and identify PeVatrons and SuperPeVatrons *secondary electrons from pγ interactions*

Clusters of Galaxies accelerating protons to 10^{18}eV

DSA acceleration of protons=> interactions of protons with 2.7K CMBR

=> e^+e^- pair production => Synchrotron and IC of secondary electrons

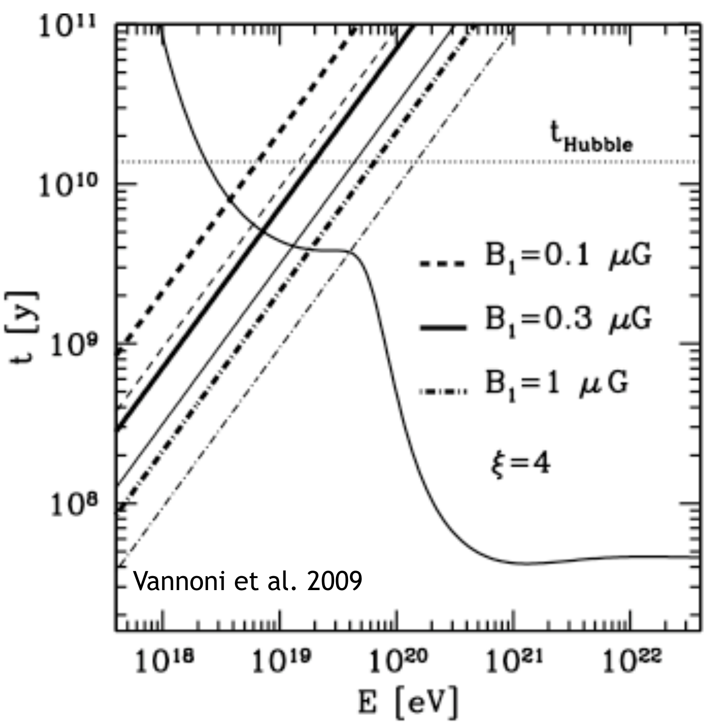


Fig. 1. Acceleration and energy loss time scales as a function of the proton energy. The acceleration time scales are obtained for the values of the upstream magnetic field B_1 reported in figure and a downstream magnetic field $B_2 = 4B_1$. The thick lines correspond to a shock velocity of 2000 km/s, the thin lines to a velocity of 3000 km/s. As an horizontal dotted line we report the estimated age of the Universe, for comparison.

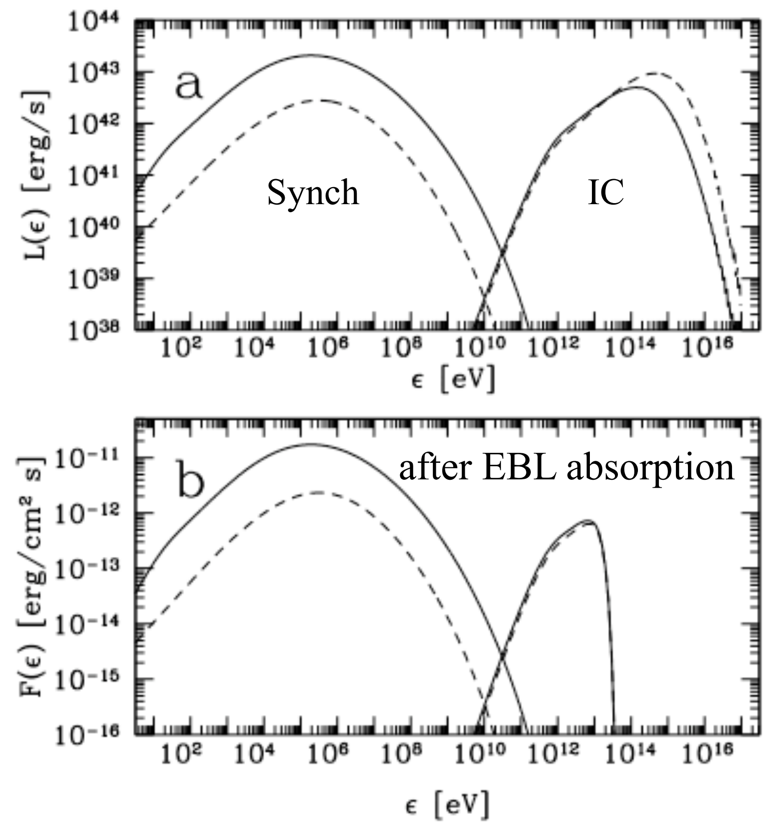
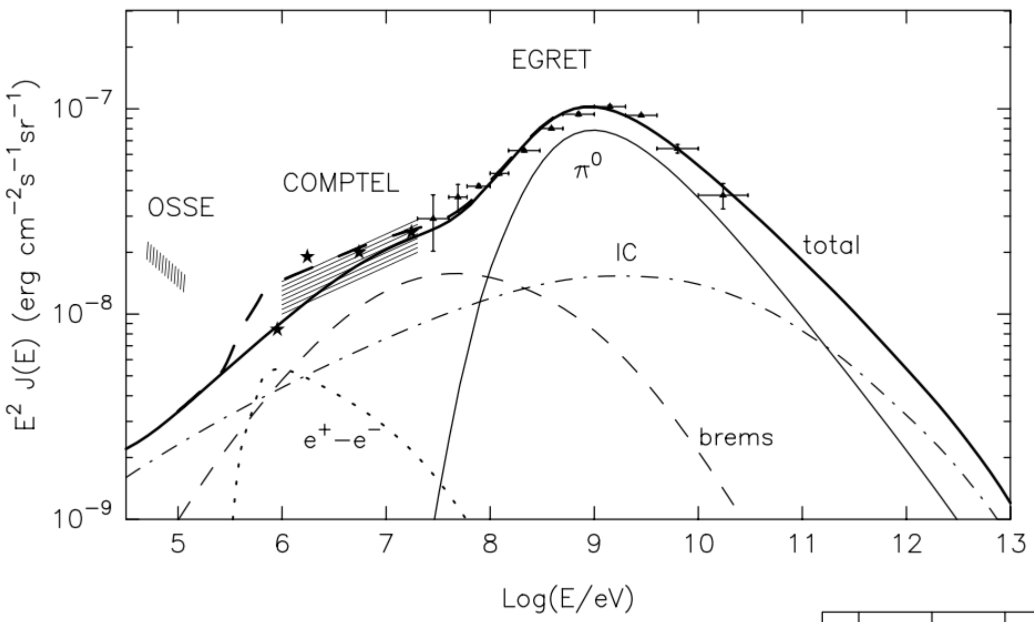
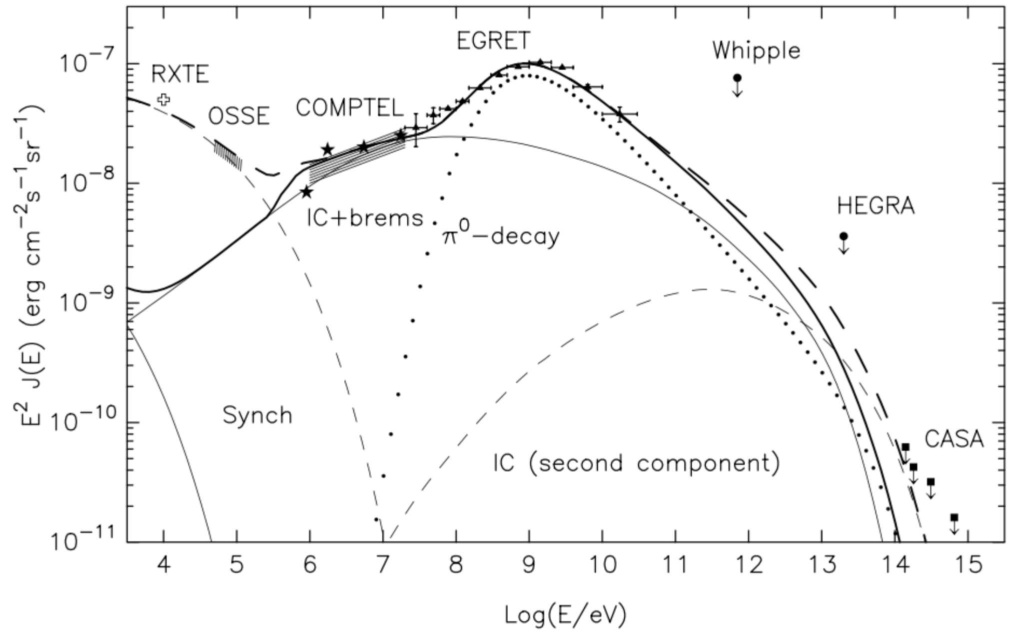


Fig. 13. a) Broadband radiation spectra produced at the source by the electron distributions in Fig. 12**b**, downstream (solid line) and upstream (dashed line). **b)** Energy flux at the observer location, after absorption in the EBL, for a source distance of 100 Mpc.



combination of several radiation mechanisms contributing to diffuse galactic (background) radiation

from 10^5 to10^{15} eV



FA, Atoyan 2000