Exploring Powerful Extragalactic Particle Accelerators with X-rays, Gamma-rays and Neutrinos

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TeV PA 2010, Paris, July 19-23

three components of Cosmic Rays

✓ below knee around 10^{15} eV

Galactic

✓ above ankle around 10^{18} eV

ExtraGalactic

✓ between knee and ankle

???

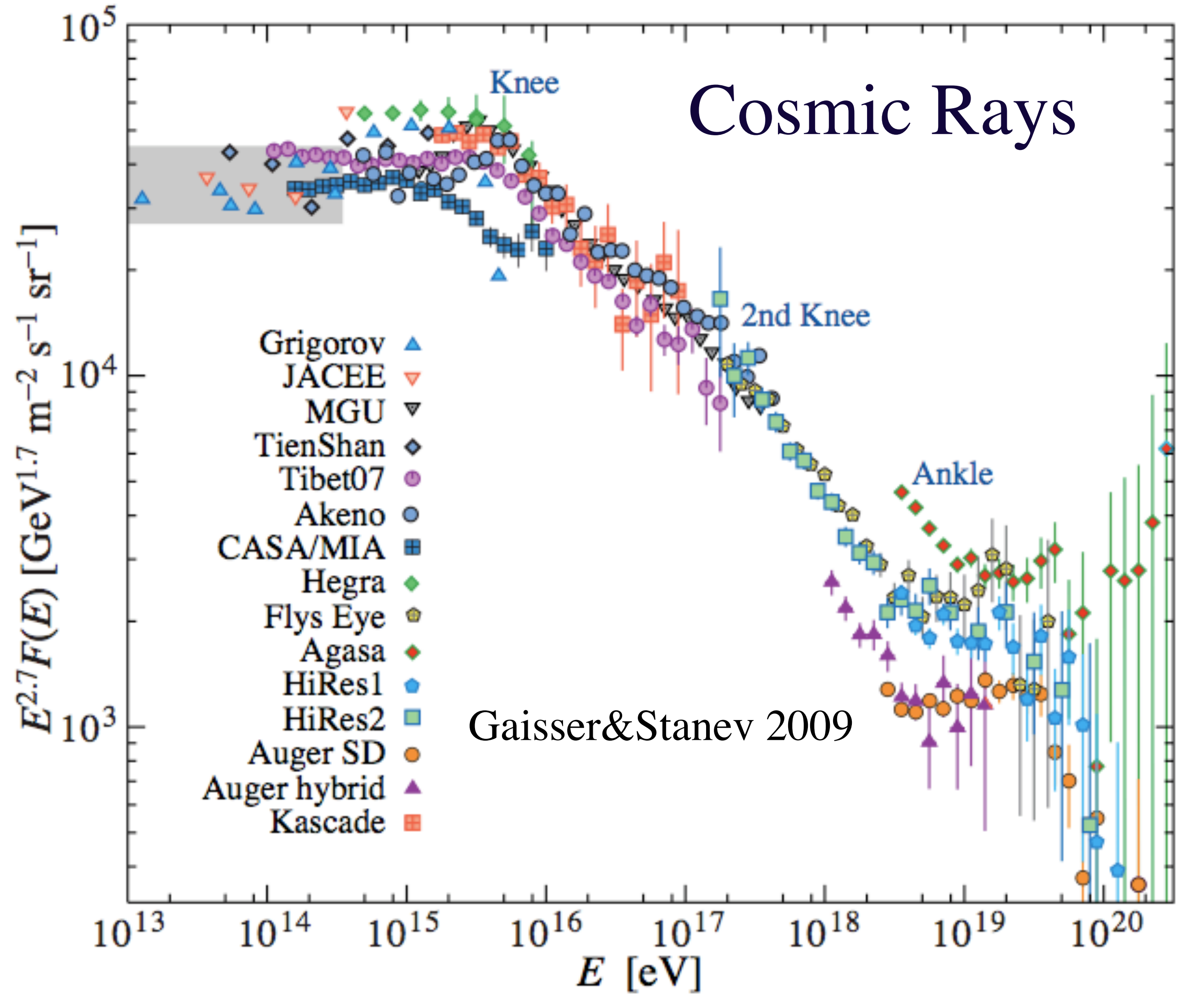


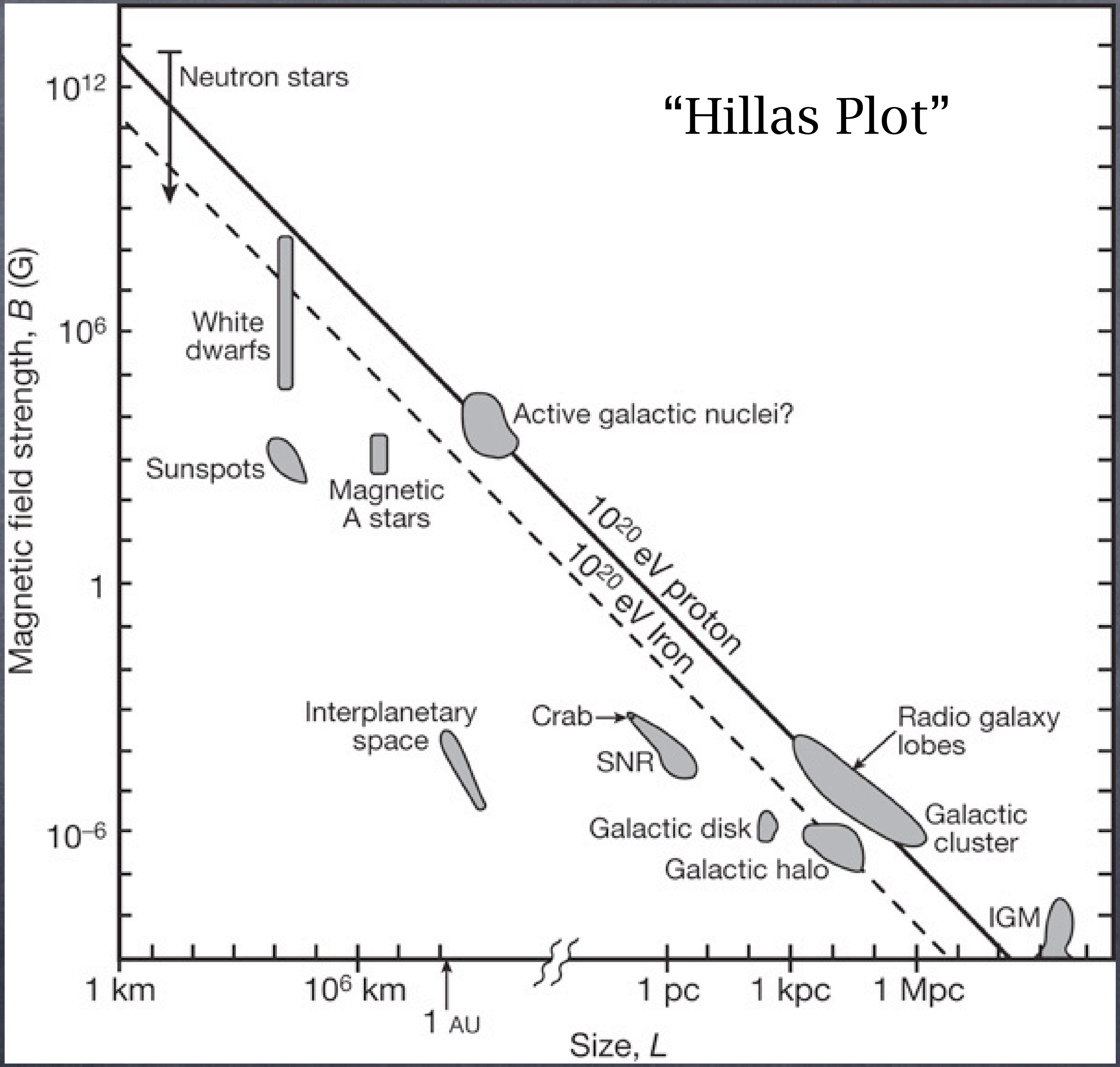
Figure 24.8: The all-particle spectrum from air shower measurements. The shaded area shows the range of the the direct cosmic ray spectrum measurements.

HiRes/AUGER confirm the existence of a spectral break/cutoff around 10^{20} eV!
is this the so-called GZK cutoff expected for the sources located beyond 100 Mpc?

not necessarily - there is another fundamental reason to expect a cutoff around 10^{20}eV because of limited efficiency for particle acceleration in available astronomical objects

suspected sites of acceleration of 10^{20} eV CRs based on the condition: size > Larmor radius:

$(R/1pc)x(B/1G) > 0.1(E/10^{20}$ eV)



PM Bauleo & JR Martino *Nature* **458**, 847-851 (2009) size > Larmor radius:

$$(R/1pc)x(B/1G) > 0.1(E/10^{20}\ eV)$$

a necessary but not sufficient condition: it implies

(1) minimum acceleration time $t_{acc}=R_L/c=E/eBc$ and
(2) no energy losses

★ the acceleration in fact is slower: $t_{acc}=(1\text{-}10)\eta\ R_L/c\ (c/v)^2$
with $\eta>1$ and shock/bulk-motion speed $v<c$ ($\eta=1$ - Bohm diffusion)

for this reason galaxy clusters cannot accelerate particles beyond 10^{19} eV

★ energy losses due to the proton synchrotron or curvature radiation in compact objects become severe limiting factor

even so, the AGN jets and GRBs are the most likely sources responsible for acceleration of 10^{20} eV protons and nuclei

Particle acceleration in Galaxy Clusters

all ingredients for effective acceleration of cosmic rays

- ✓ formation of strong accretion shocks
- ✓ magnetic field of order 0.1-1 μG
- ✓ shock velocity - few 1000 km/s
- ✓ acceleration time ~ Hubble time

but protons cannot be accelerated to 10^{20} eV

Proton Spectrum

pair production losses shape the proton spectrum around the cut-off:

- small bump,
- non-exponential cut-off

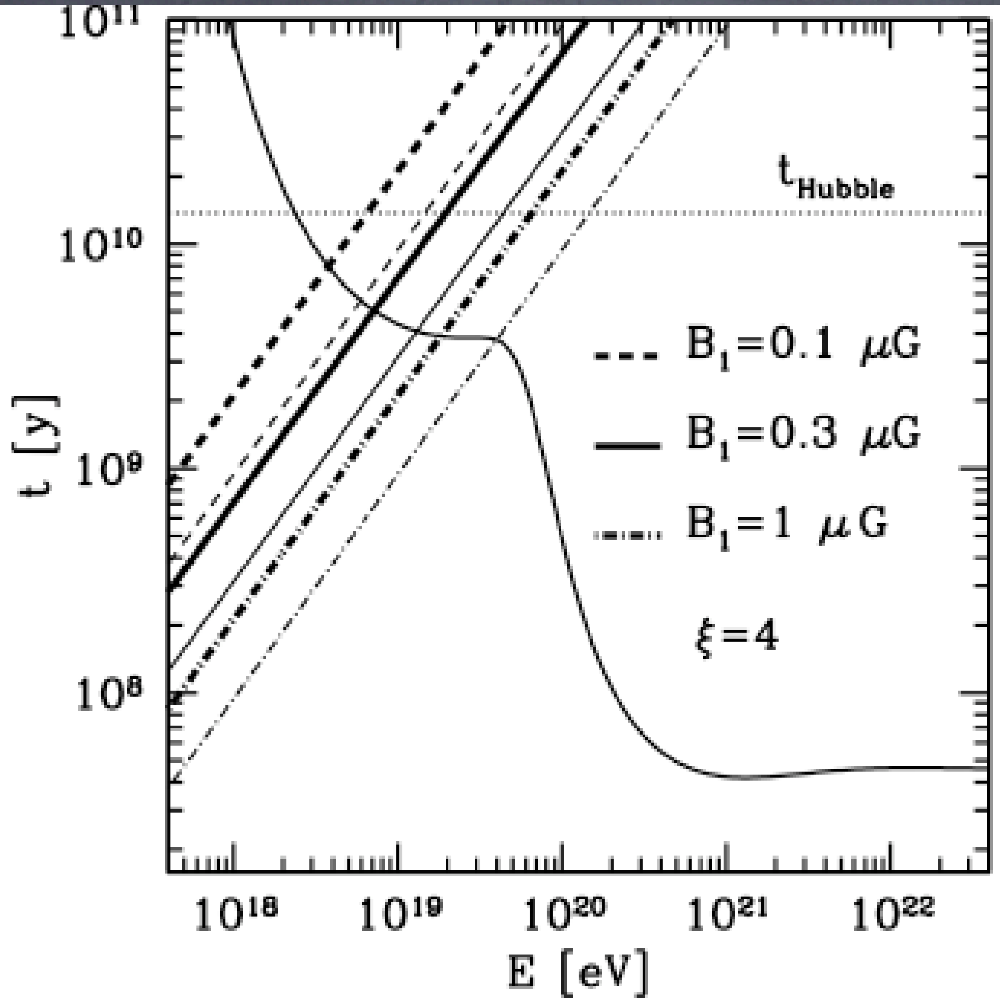


Fig. 1. Acceleration and energy loss time scales as a function of the proton energy. The acceleration time scales are obtained for the values of the upstream magnetic field B_1 reported in figure and a downstream magnetic field $B_2 = 4B_1$. The thick lines correspond to a shock velocity of 2000 km/s, 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.

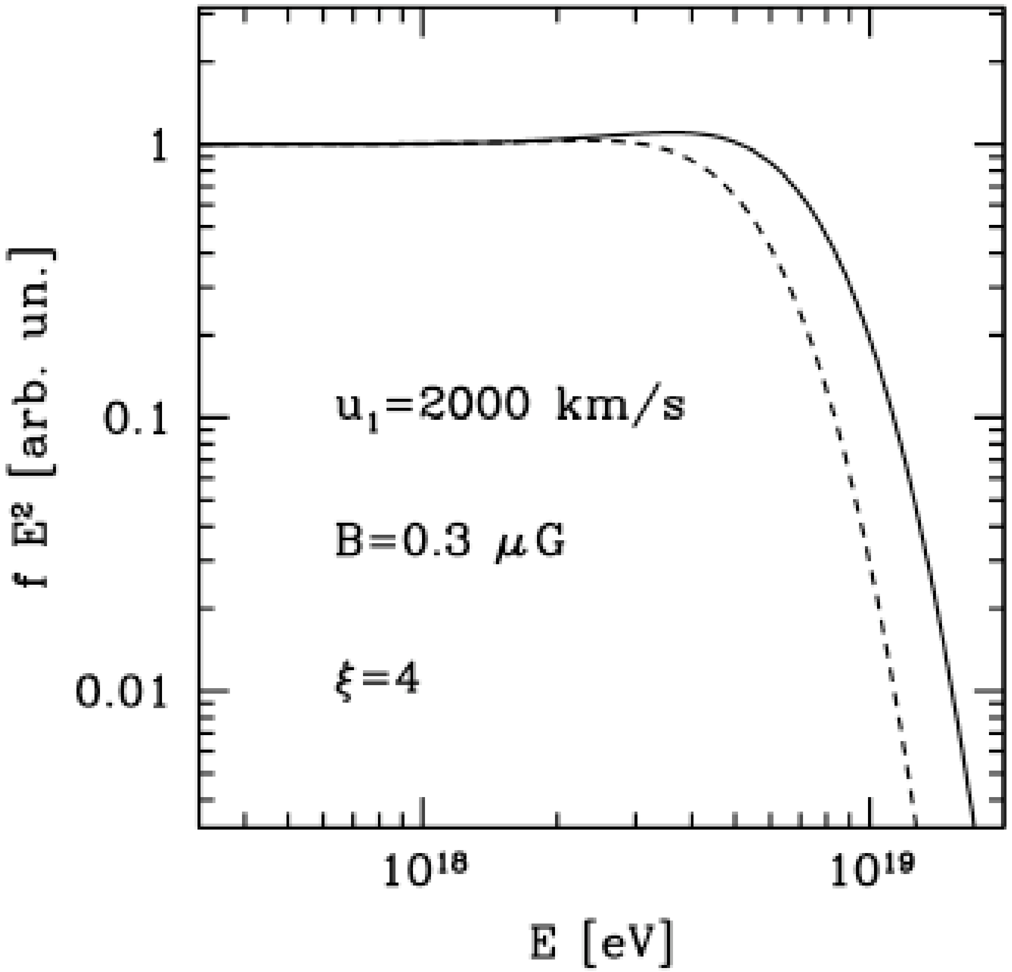


Fig. 2. Proton spectra at the shock location for an acceleration time of 10 Gyr (solid line) and 5 Gyr (dashed) for a shock velocity of 2000 km/s, a magnetic field upstream $B_1 = 0.3$ μG and a magnetic field downstream $B_1 = 4B_1$.

Vannoni, FA, Gabici 2009

acceleration sites of 10^{20} eV CRs

$$t_{\rm acc} = \frac{R_L}{c}\eta^{-1}$$

signatures of extreme accelerators?

✓ synchrotron self-regulated cutoff:

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

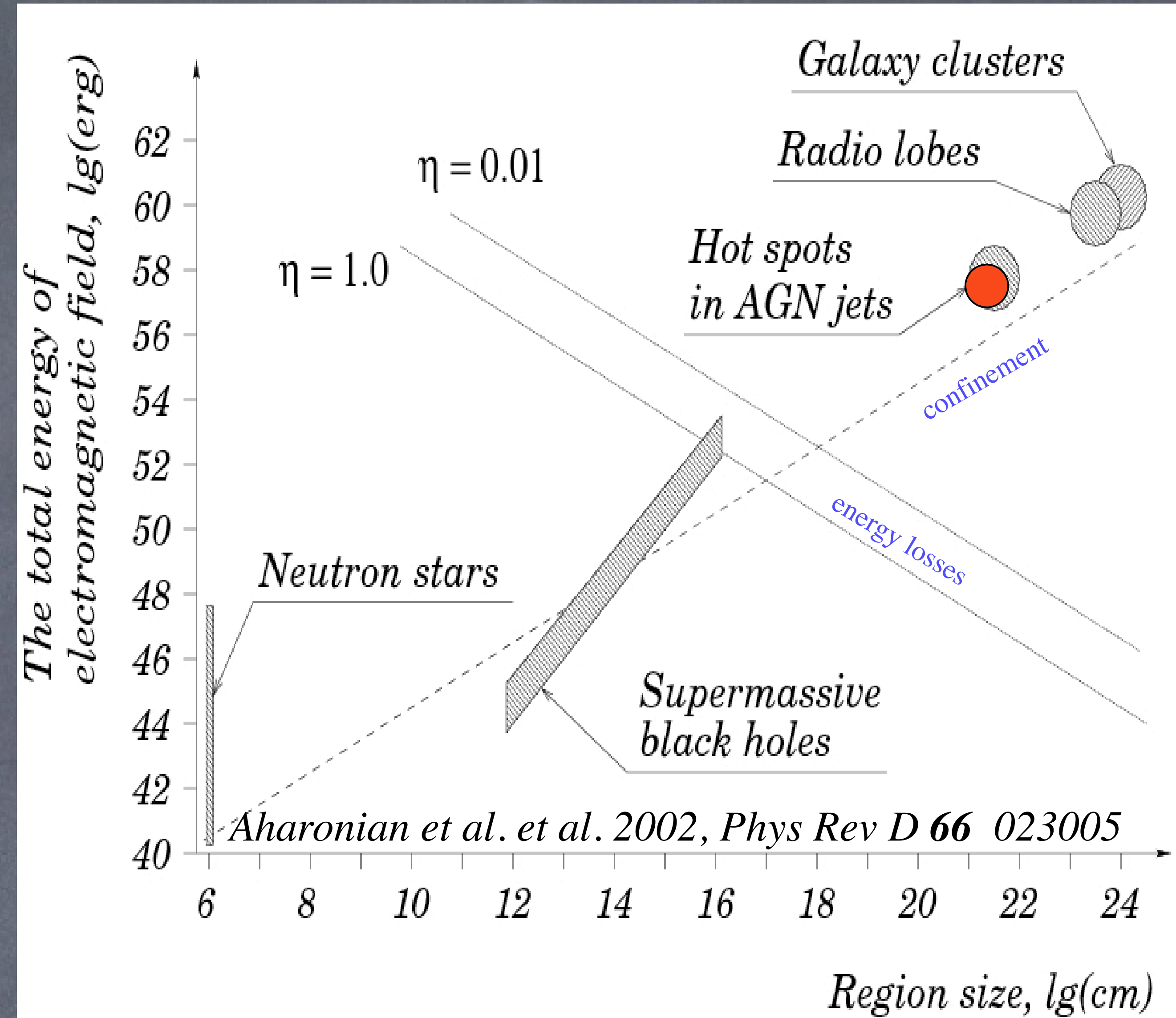
$\simeq$ 300GeV proton synchrotron
$\simeq$ 150MeV electron synchrotron

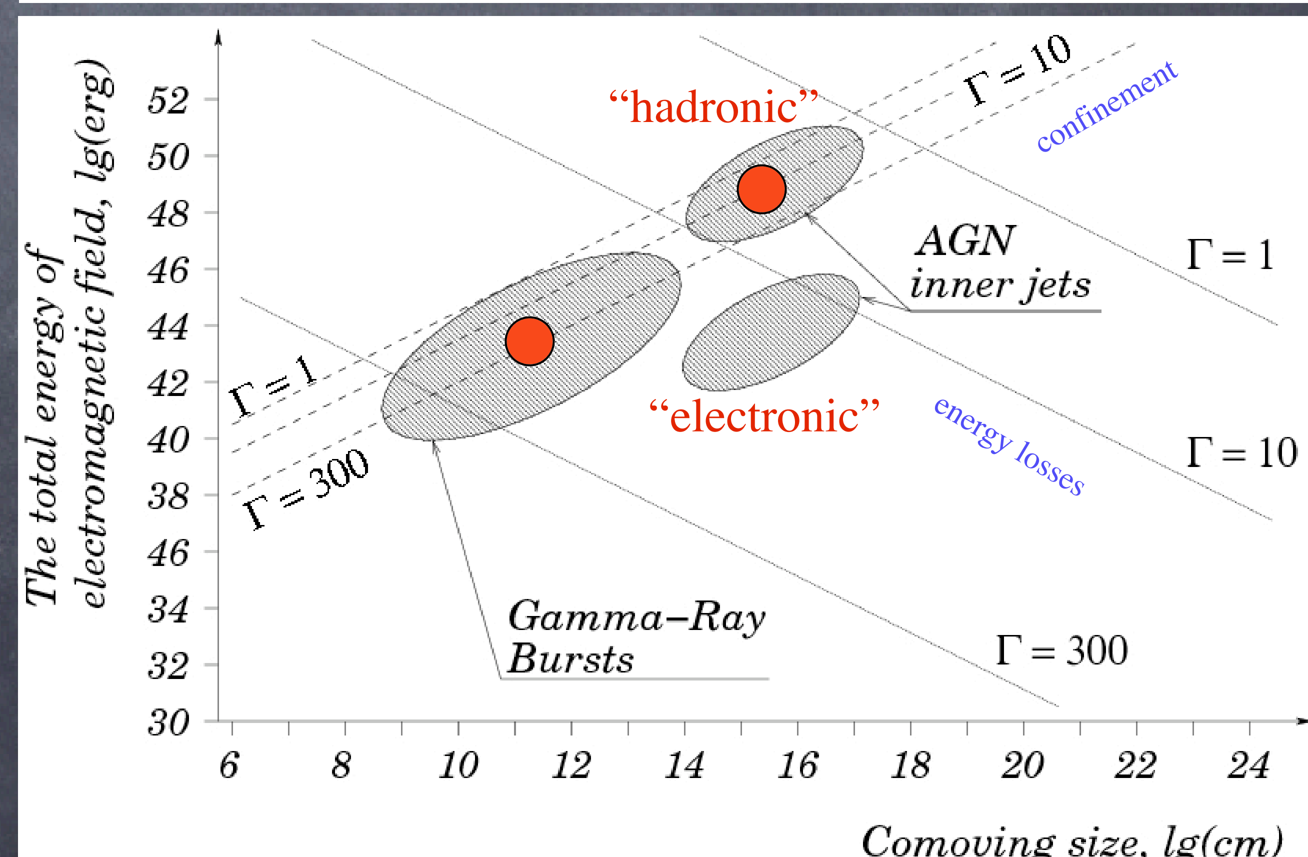
✓ neutrinos (through "converter" mechanism)
production of neutrons (through p interactions) which travel without losses and at large distances convert again to protons => ^{2} energy gain !

Derishev, FA et al. 2003, Phys Rev D ***68*** *043003*

✓ observable off-axis radiation
radiation pattern can be much broader than 1/

Derishev, FA et al. 2007, ApJ, ***655****, 980*





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compact/magnetized objects!

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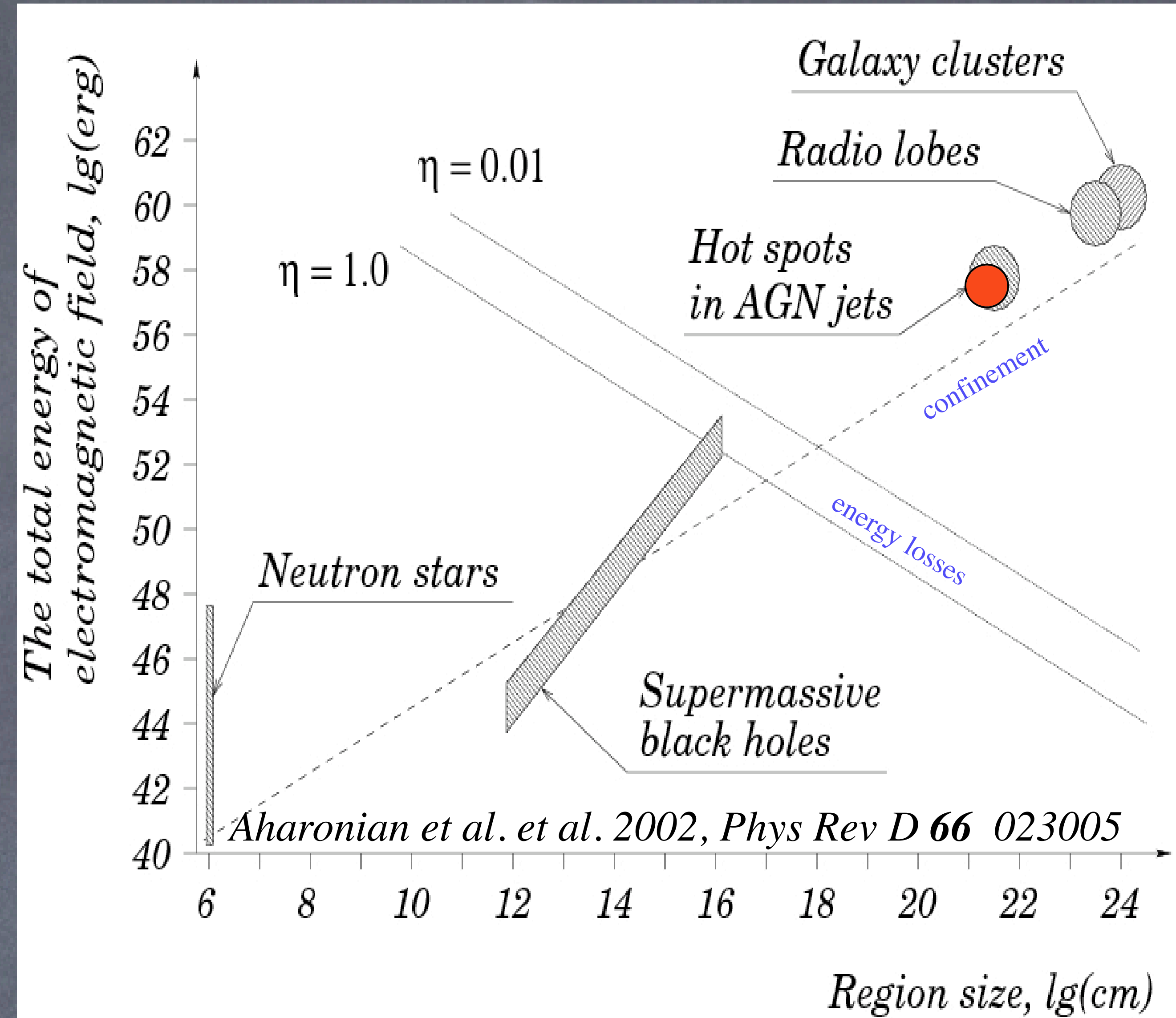
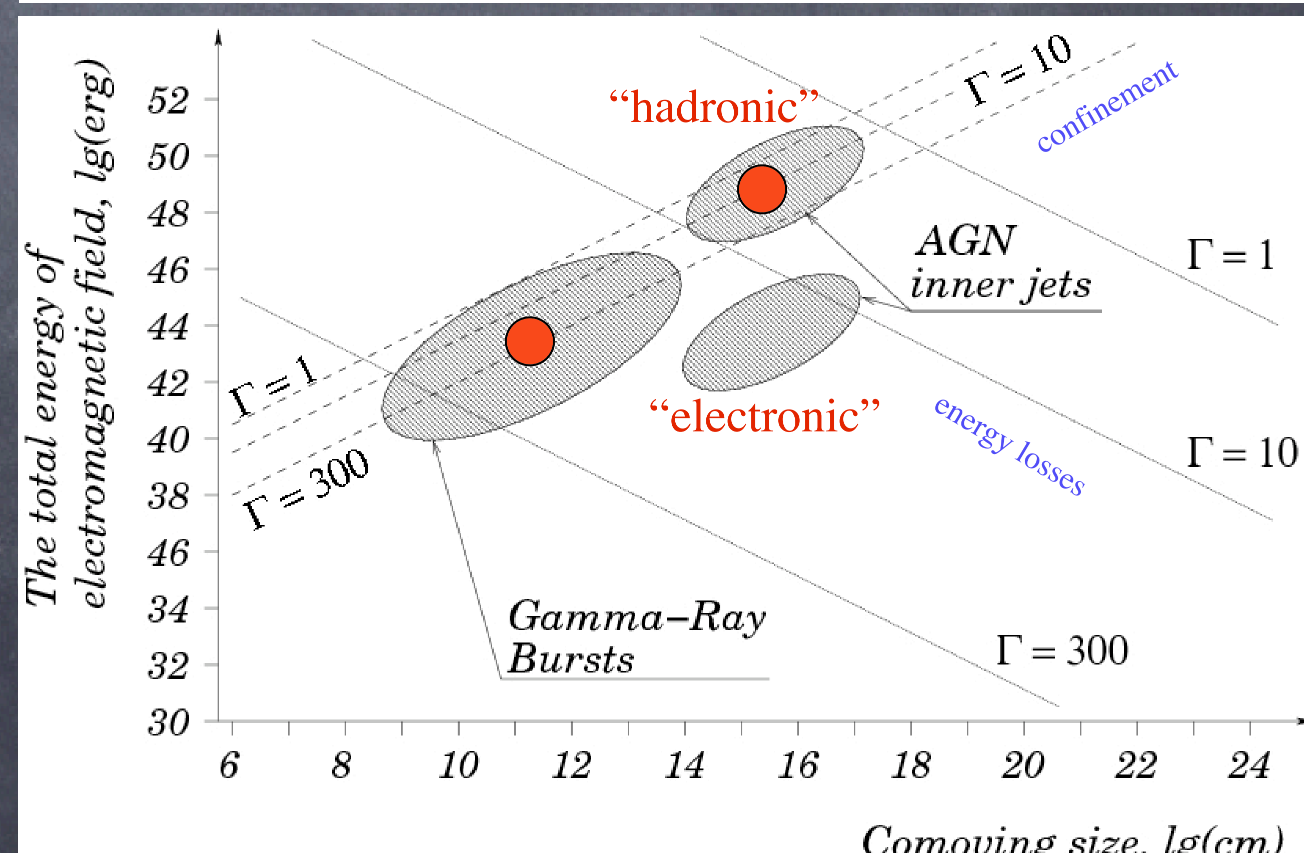
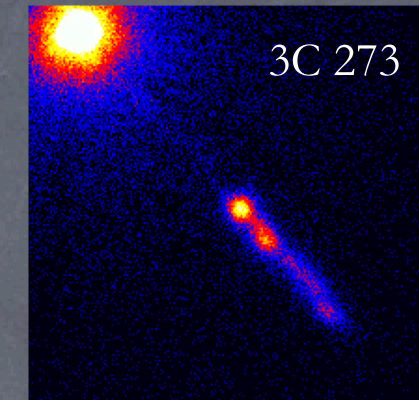




acceleration and radiation of UHE protons in kpc-scale structures of AGN jets



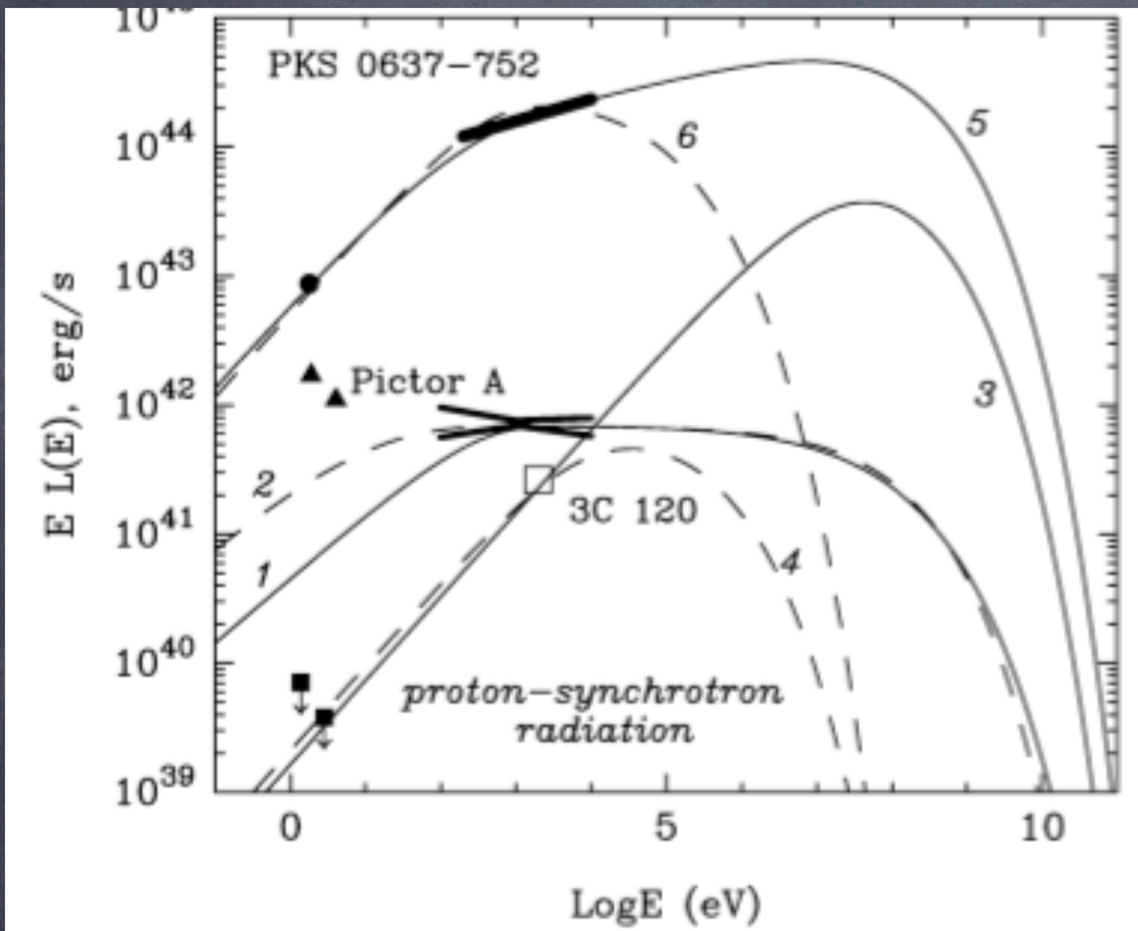


Figure 1. Proton synchrotron luminosities of jet features in Pictor A (western radio hotspot), 3C 120 (25-arcsec radio knot), and PKS 0637-752 (the outer jet component). The model parameters are described in the text. The optical and X-ray data are from Wilson et al. (2001) for Pictor A; Harris et al. (1999) for 3C 120; Schwartz et al. (2000) for PKS 0637-752.

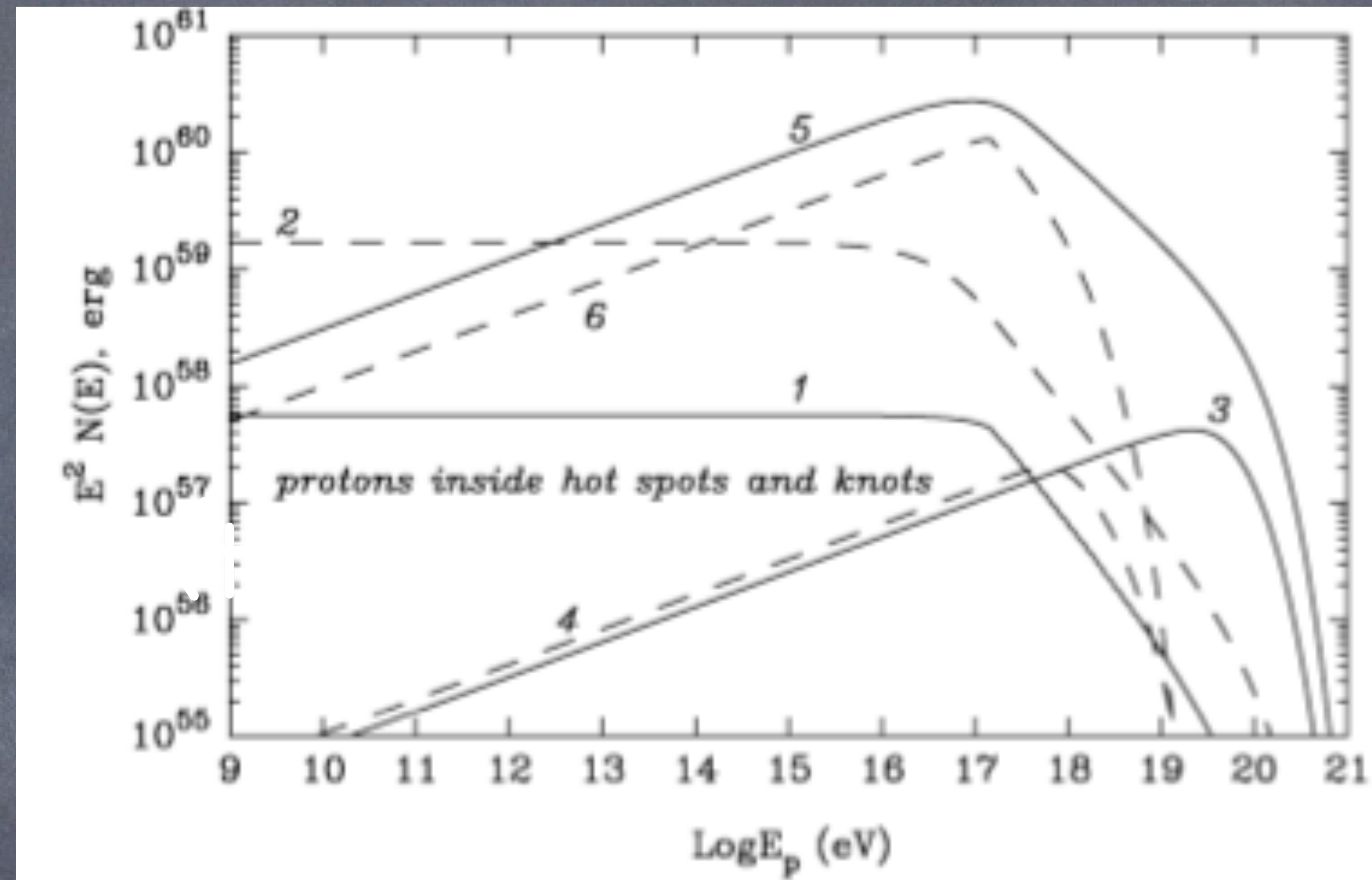
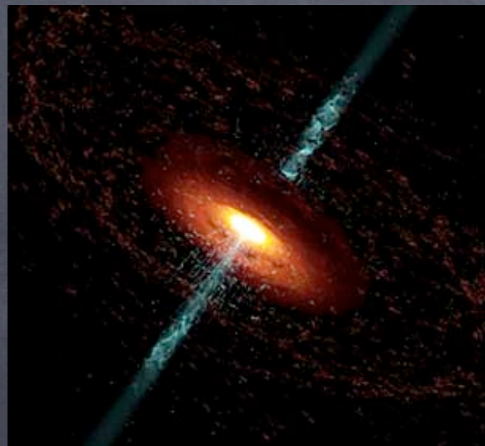


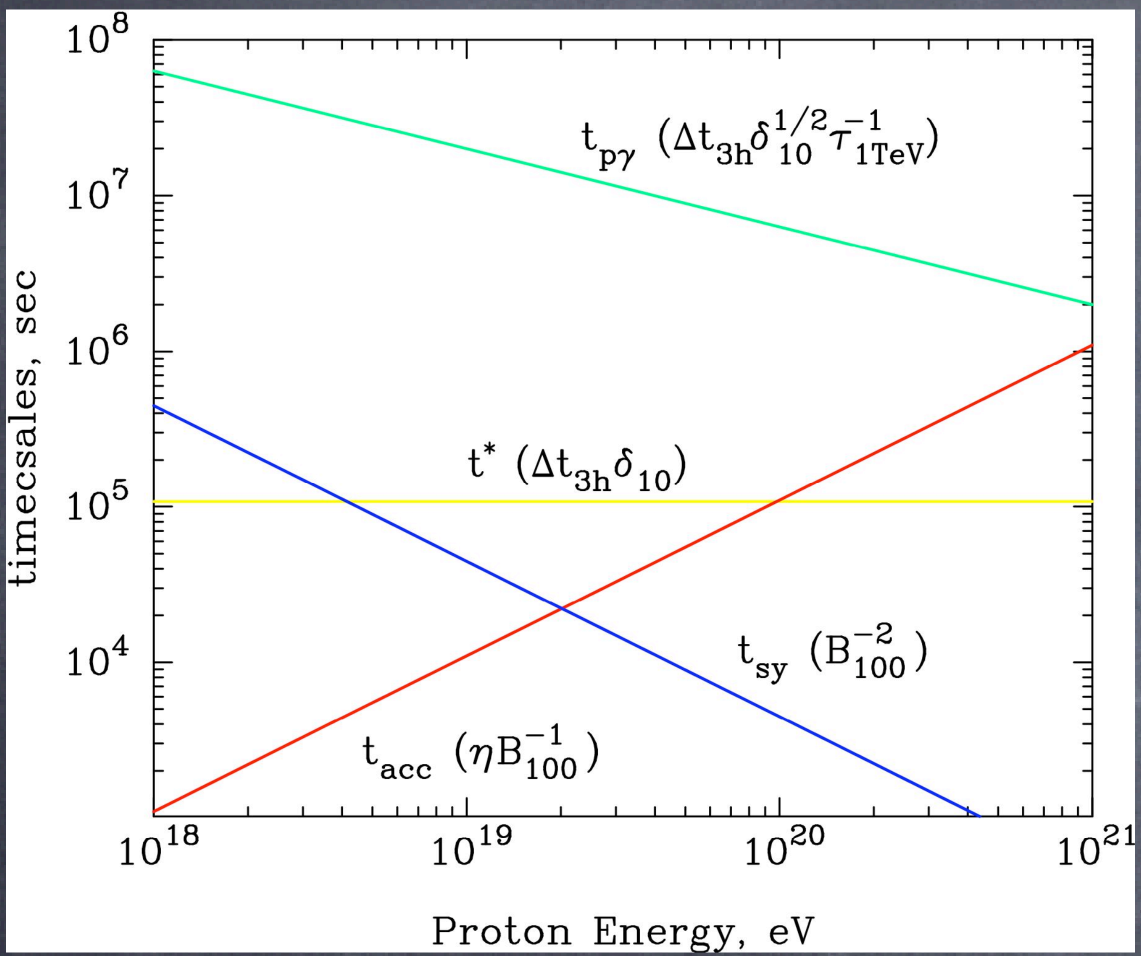
Figure 2. Total energy of relativistic protons confined in X-ray-emitting regions of radio jets: the western hotspot in Pictor A (curves 1 and 2), 25-arcsec knot of 3C 120 (curves 3 and 4), and the outer jet component in PKS 0637-752 (curves 5 and 6).

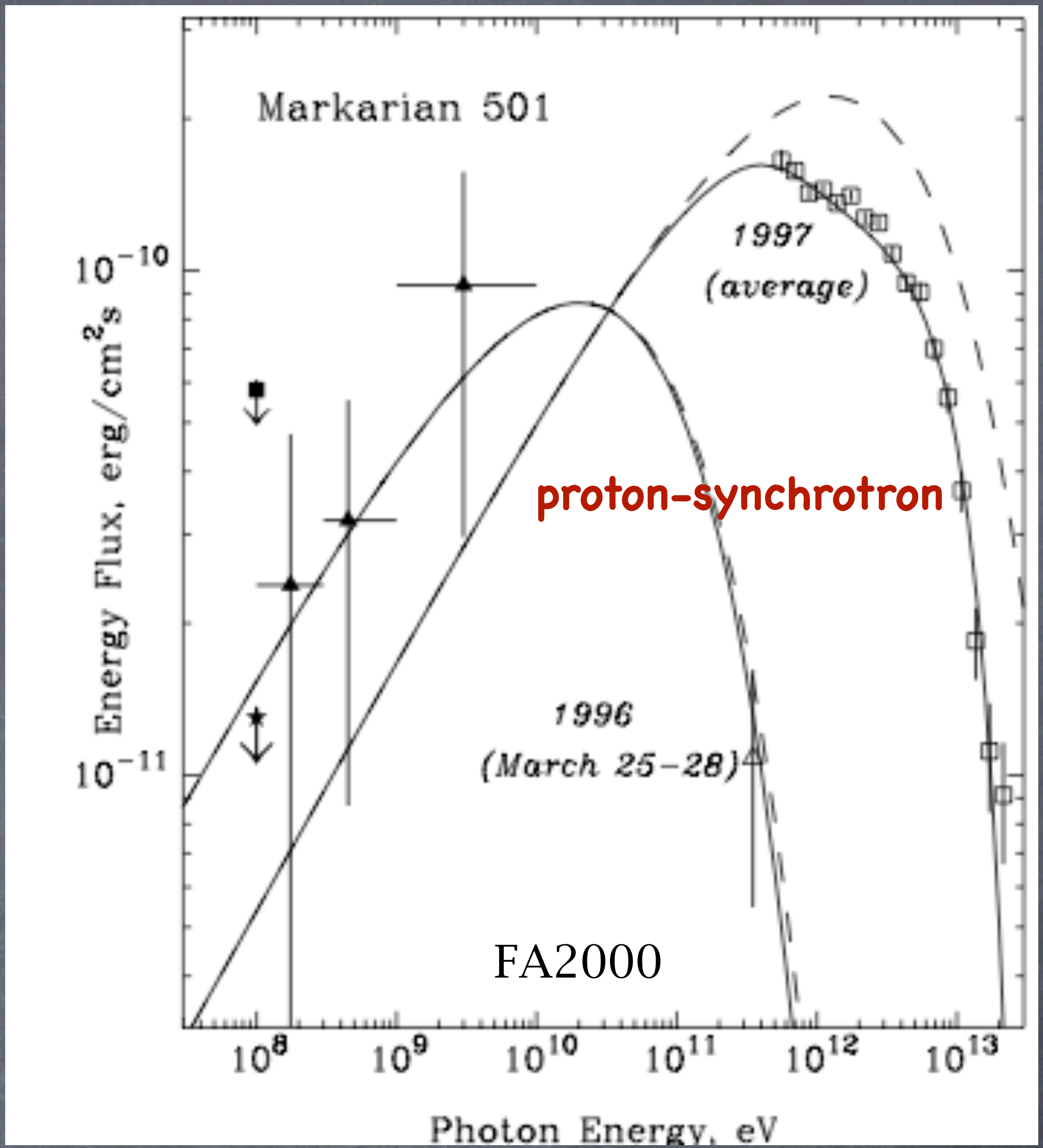
FA 2002

$(R/1\text{kpc})\times(B/100\mu\text{G}) > 1(E/10^{20}\text{ eV})$: protons can be acceleared to 10^{20} eV e.g. by relativistic shocks



acceleration/radiation of > 10^{19}eV protons in sub-parsec AGN jets





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} δ GeV

requires extreme accelerators: $\eta \sim 1$

proton astronomy?

✓ because of interstellar and intergalactic magnetic fields, the information about the original directions of cosmic rays pointing to their production sites is lost

✓ the flux of cosmic rays is contributed, most likely, by a large number of galactic and extragalactic sources; these objects represent different source populations characterized by essentially different physical parameters – age, distance, energy budget, etc., as well as by different particle acceleration scenarios

=> extremely difficult the identification of sources of the isotropic flux of cosmic rays based on two measurables - the chemical composition and energy spectra of particles - characterizing the "soup" cooked over cosmological timescales

but .... at extremely high energies, $E \sim 10^{20}$ eV, the impact of galactic and extragalactic magnetic fields on the propagation of cosmic rays becomes less dramatic, which might result in large and small scale anisotropies of CR flux

depending on the strength and structure of the (highly unknown) intergalactic magnetic field, the highest energy domain of CRs may offer us a new astronomical discipline - "cosmic ray astronomy", provided that $B_{IGM} < 10^{-9}$ G

10^{20} eV - a special energy

extension of studies to energies 10^{20}eV and beyond enhances chances of localization of particle accelerators for three independent reasons:

- with an increase of energy, the probability that a proton of 10^{20}eV would penetrate through IGM without significant deflections in chaotic magnetic fields increases; for IGMF << 10^{-9}G, the deflection angle can be quite small also for lower energies, but 10^{20} eV is a special energy because
- deflection of protons with energy less than 10^{20} eV in galactic magnetic fields exceeds 1 degree (angular resolution of UHE cosmic ray detectors)
- particles of such high energies can arrive only from relatively nearby accelerators located within 100 Mpc. this dramatically (by orders of magnitude) decreases the number of relevant sources of $\geq 10^{20}$eV protons contributing to the observed cosmic ray flux, and correspondingly reduces the level of the diffuse background, i.e. the (quasi) isotropic flux due to superposition of contributions by unresolved discrete sources.

Angular, spectral, and time distributions of highest energy protons and associated secondary gamma-rays and neutrinos propagating through extragalactic magnetic and radiation fields

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(Dated: June 8, 2010)

The angular, spectral and temporal features of the highest energy protons and accompanying them secondary neutrinos and synchrotron gamma-rays propagating through the intergalactic magnetic and radiation fields are studied using the analytical solutions of the Boltzmann transport equation obtained in the limit of the small-angle and continuous-energy-loss approximation.

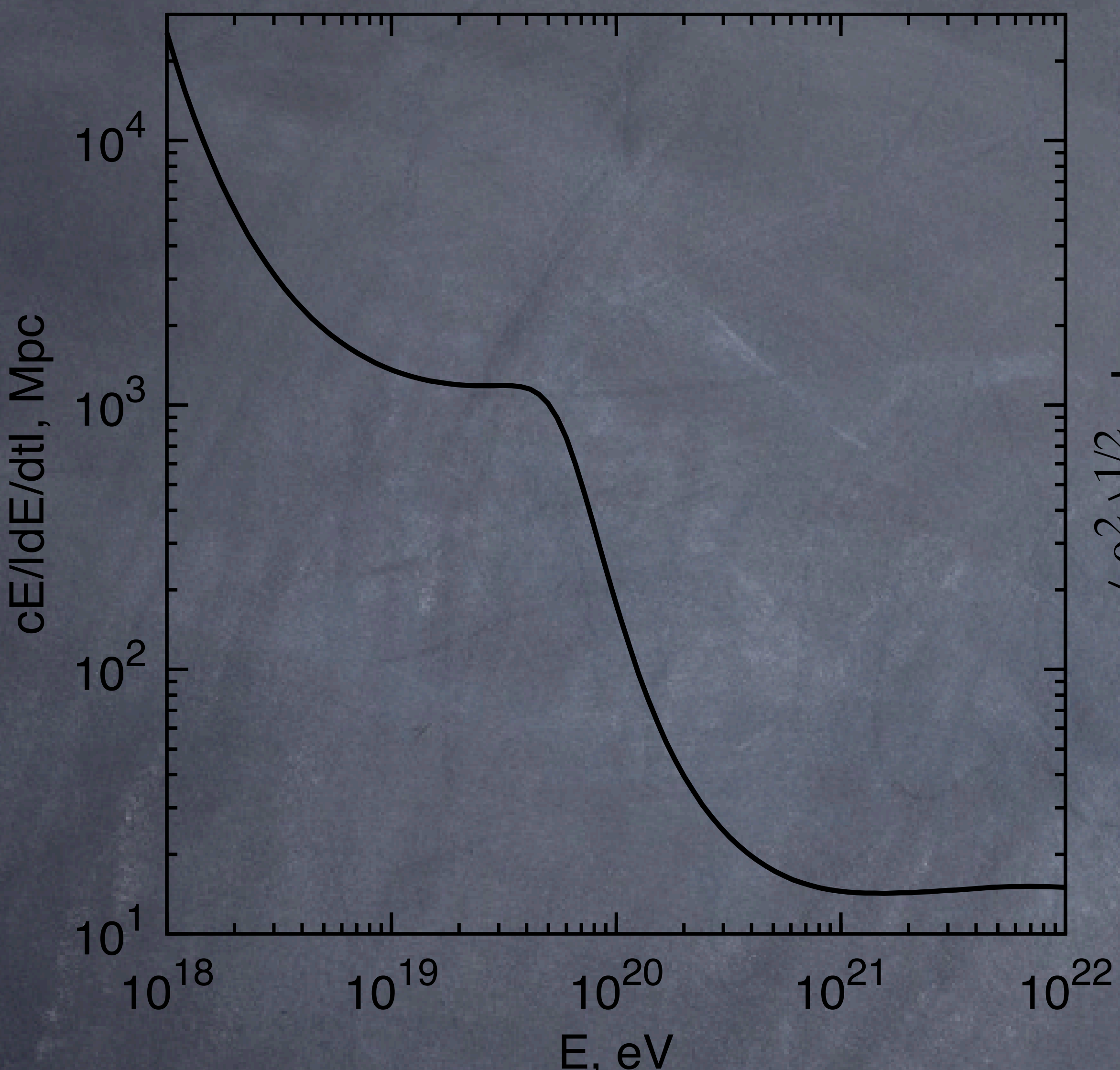
PACS numbers: 96.50.sb, 13.85.Tp, 98.70.Sa, 98.70.Rz

I. INTRODUCTION

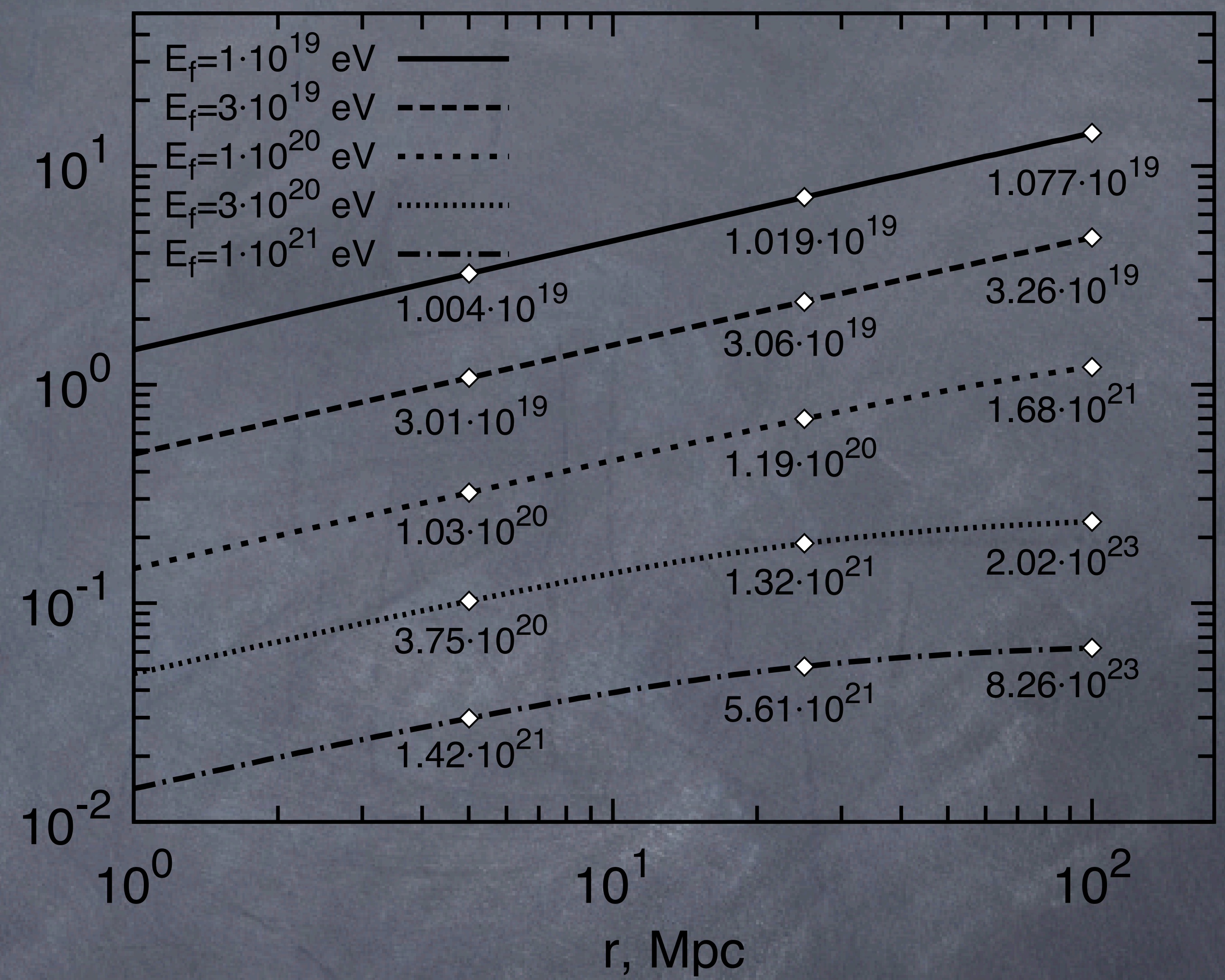
Because of deflections in the interstellar and intergalac-

protons ($\theta \propto B/E$). However at energies significantly below 10^{20} eV, the deflection in galactic magnetic fields becomes the dominant factor leading to the lost of information about the original directions of particles (see, e.g., Ref. [1])

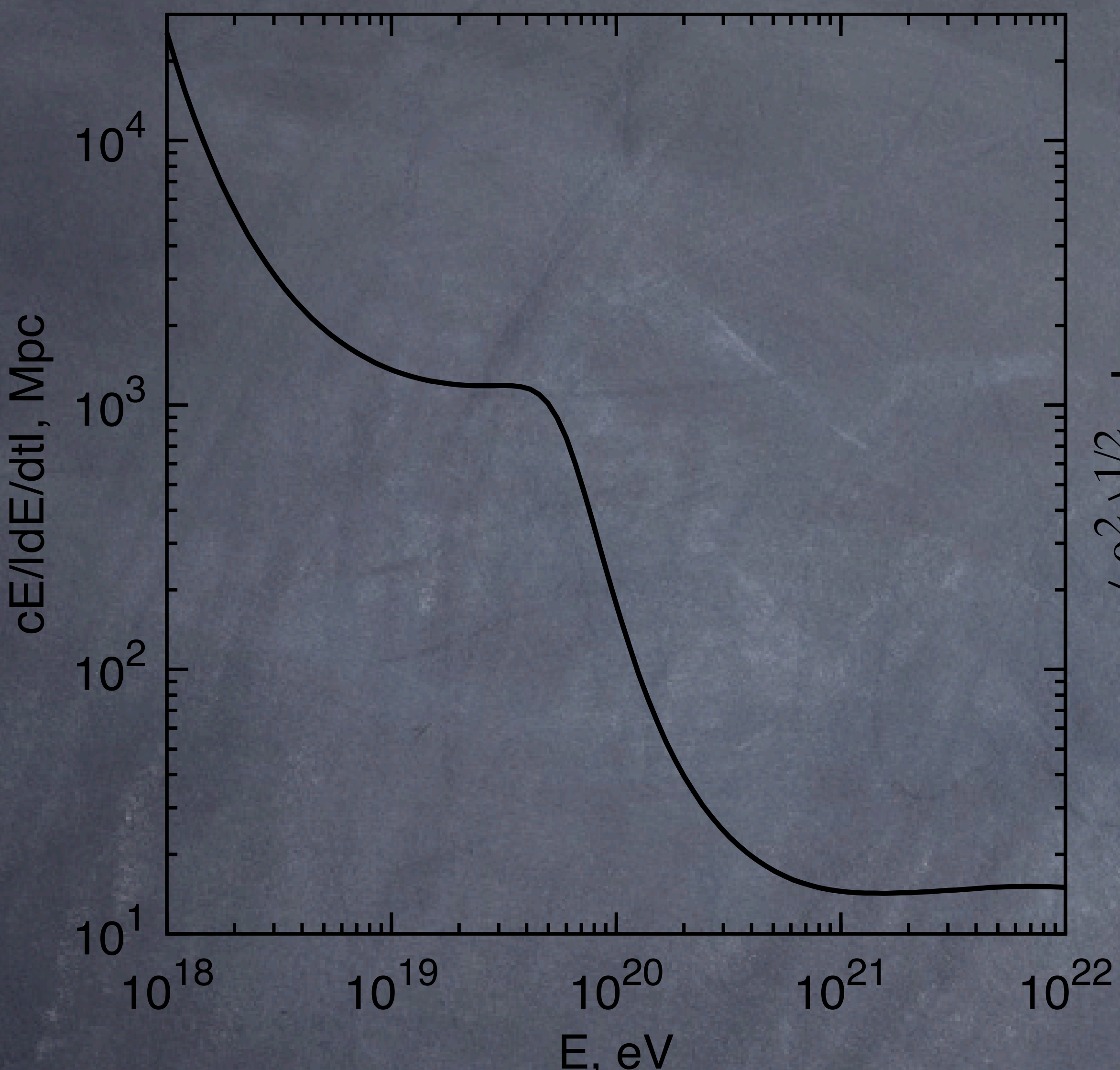
to appear in Phys Rev D, 2010 Aug 10 issue



mean free path of protons in IGM due to interactions with CMBR at z<<1



mean deflection angle of protons for fixed final (observed) energy **E_f** for IGM B=1 nG; λ=1Mpc. Numbers at curves are energies of protons at distance **r** from the observer detection of 10^{21}eV protons very important!



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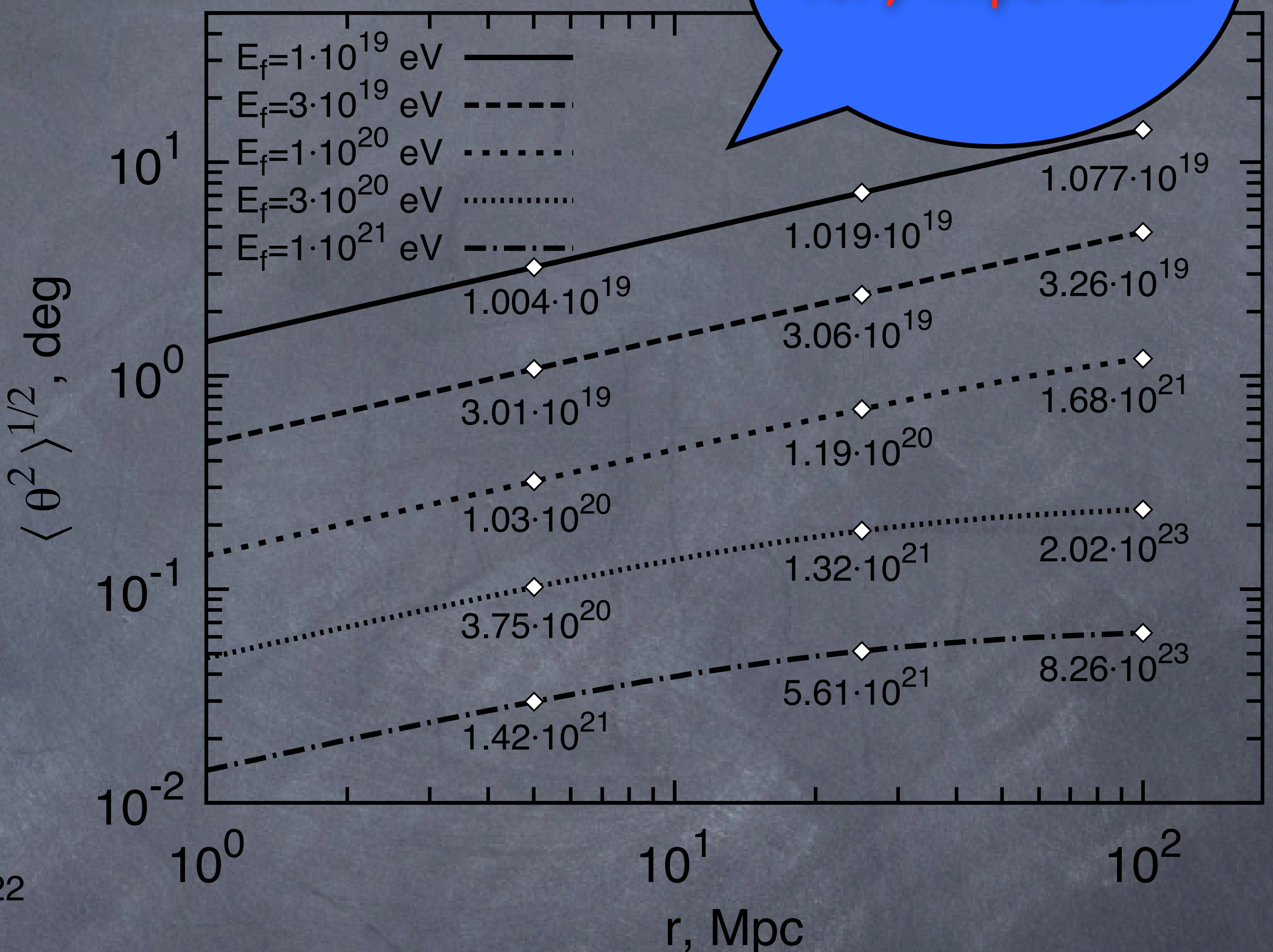
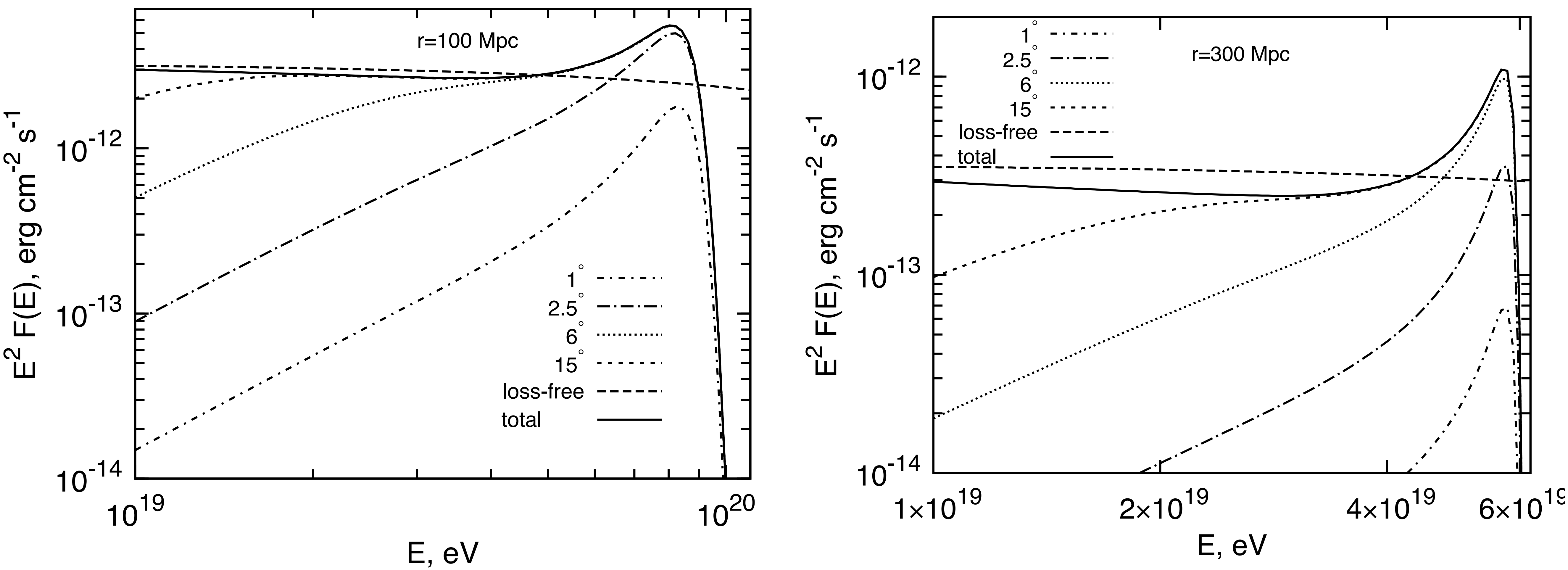


mean deflection angle of protons for fixed final (observed) energy **E_f** for IGM B=1 nG; λ=1Mpc. Numbers at curves are energies of protons at distance **r** from the observer

energy spectra of protons within different solid angles



$dN/dE = AE^{-\alpha} \exp(-E/E_o); \alpha=2,\ Eo=3x10^{20}eV;$

$L_p=10^{44}$ erg/s; B=1nG; λ=1Mpc

"bump" (just before the cutoff) - due to interactions with CMBR

"sharp maximum" - due to the magnetic "filter"

for B between 10^{-9} to 10^{-7} G electrons are produced within 10 Mpc and radiate predominantly through synchrotron radiation before any significant deflection
=> point-like GeV/TeV gamma-rays and EeV neutrinos (FA 2002; Gabici&FA 2005)

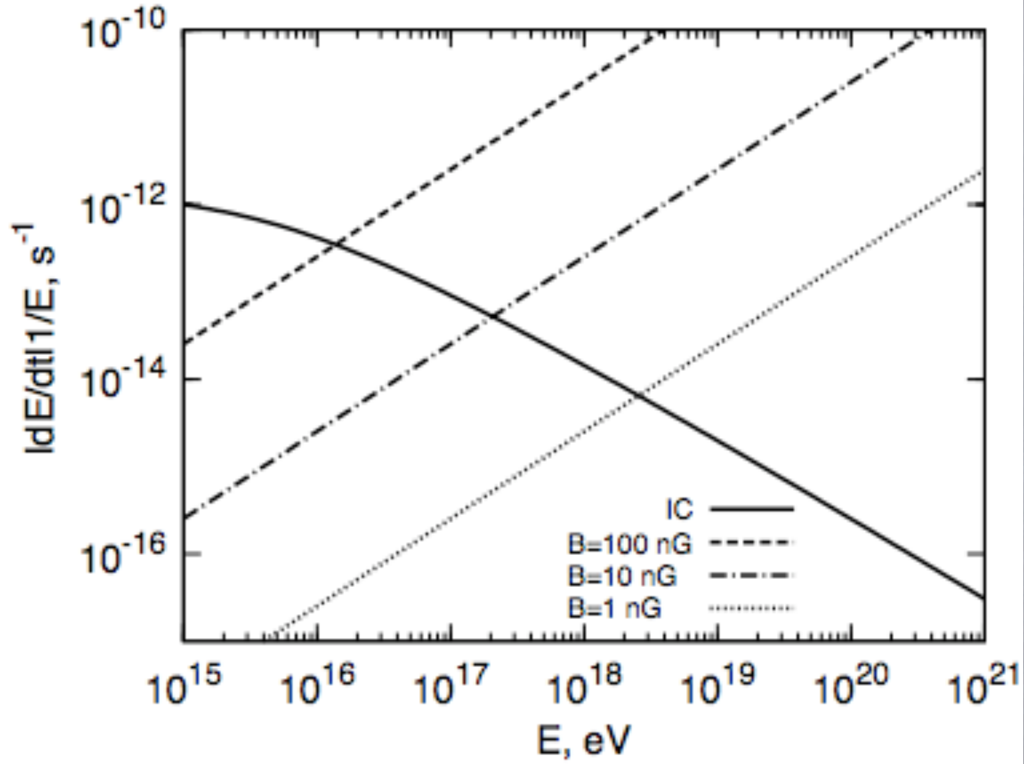


FIG. 4: Energy loss rates of electrons due to inverse Compton scattering on CMBR photons (solid line) and synchrotron radiation in random magnetic field for $B = 1$ nG, 10 nG, and 100 nG. For electrons of energy $E \gtrsim 10^{19}$eV the inverse Compton scattering on the radiowaves of CRB becomes comparable or even can exceed the contribution of the Compton scattering on CMBR, however for IGMF $B \gtrsim 1$ nG the synchrotron radiation remains the main cooling channel.

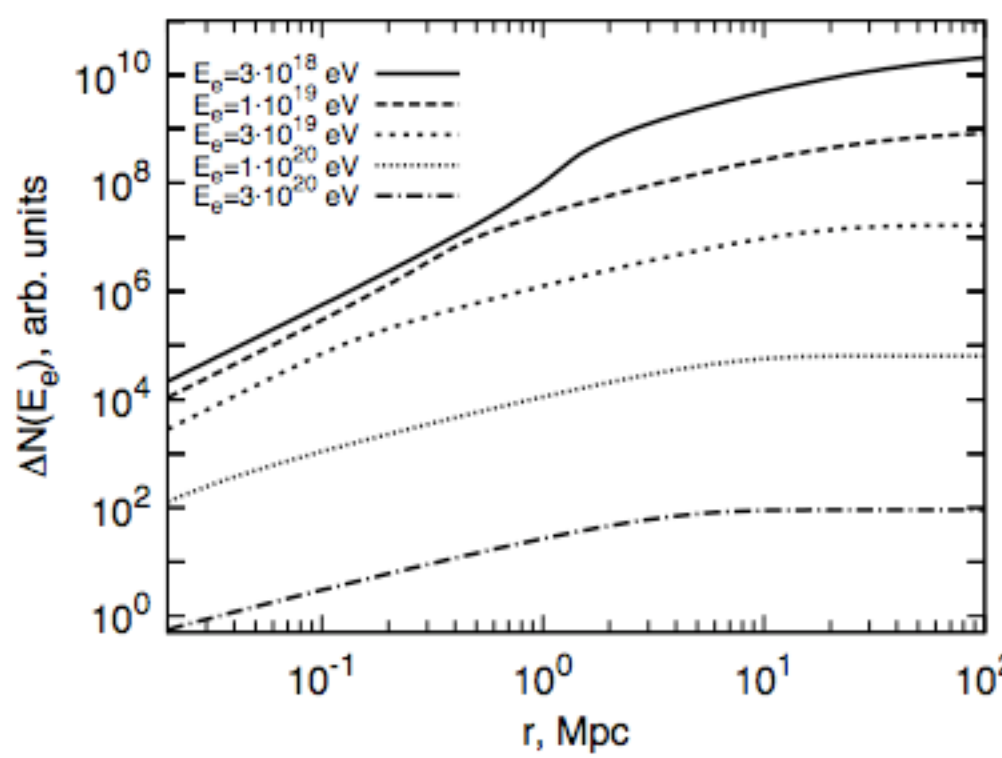
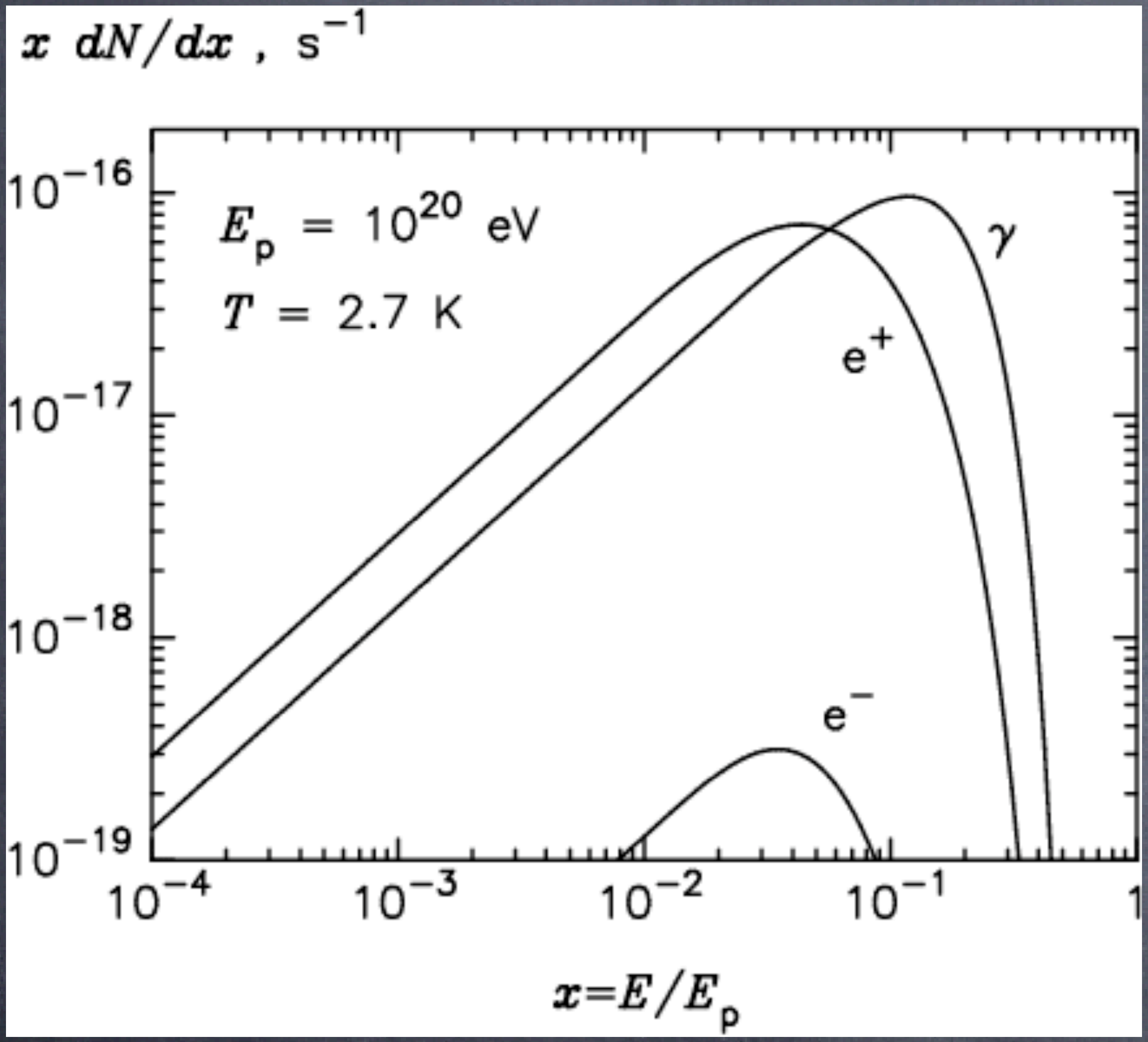
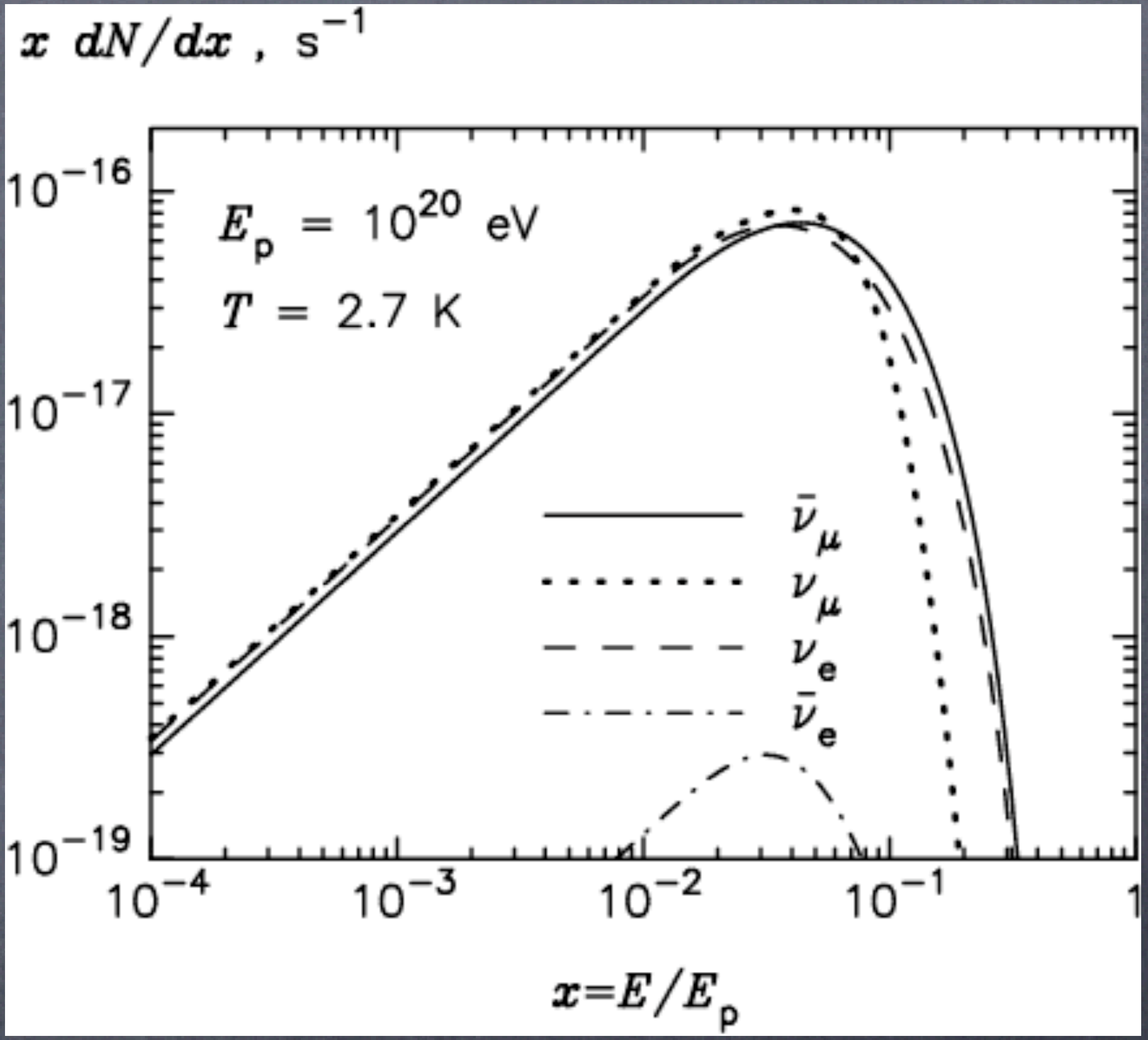


FIG. 5: Number of electrons of energy E_e located inside a sphere of the radius r.

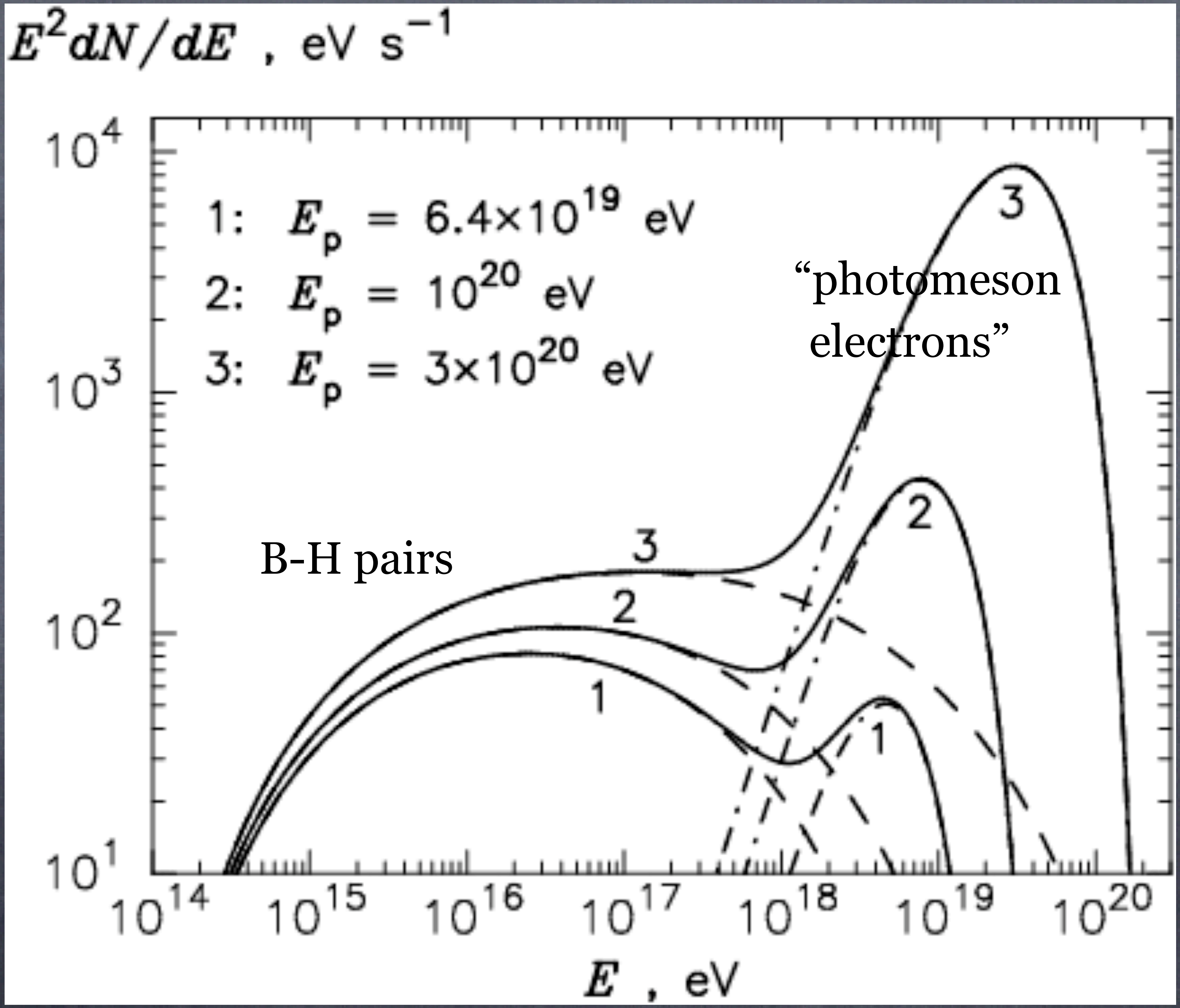
distributions of secondary photons, electrons, neutrinos from photomeson interactions





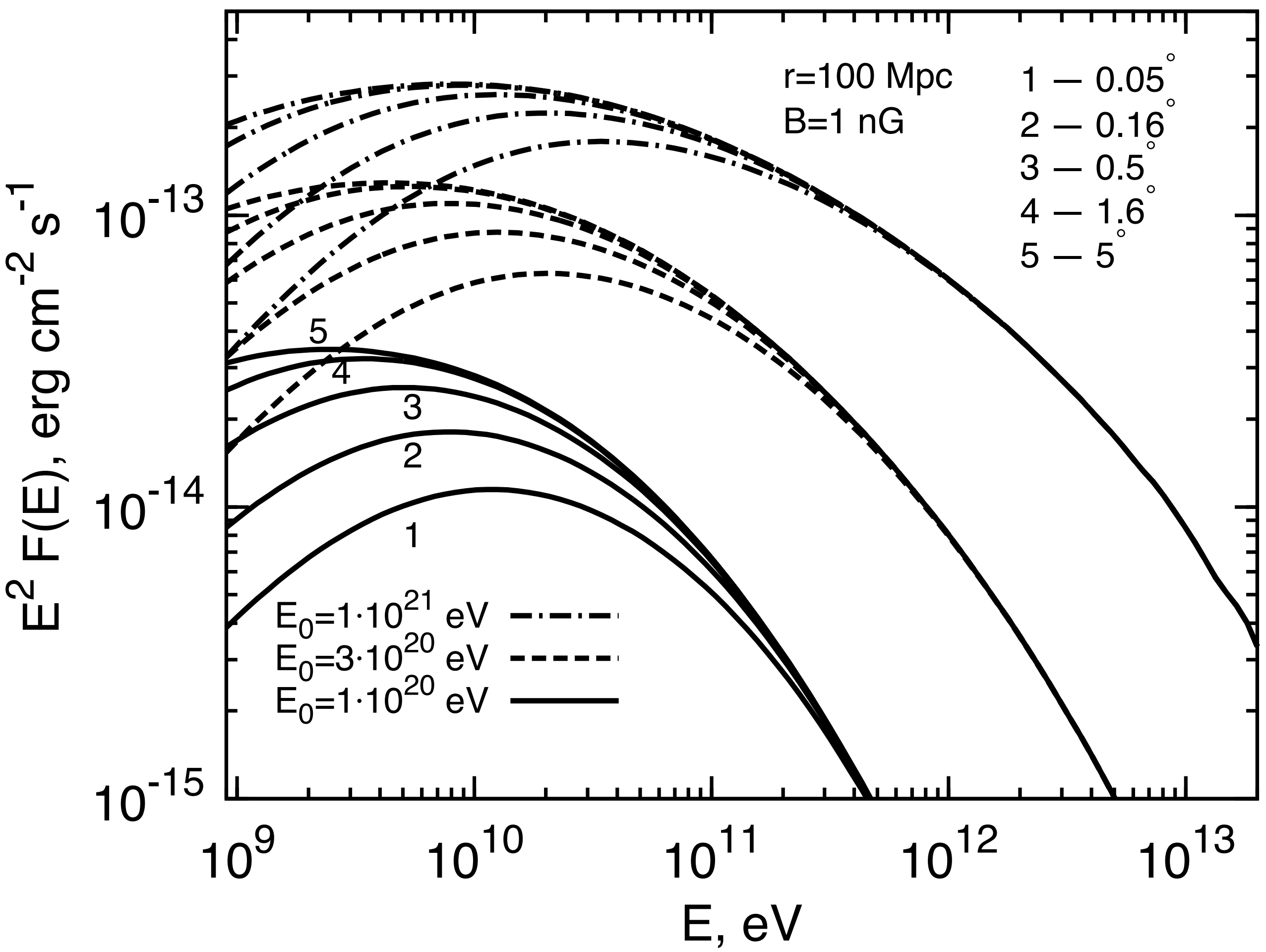
second generation of electrons from (B-H) pair production of γ-rays more important than the contribution from the first generation of electrons

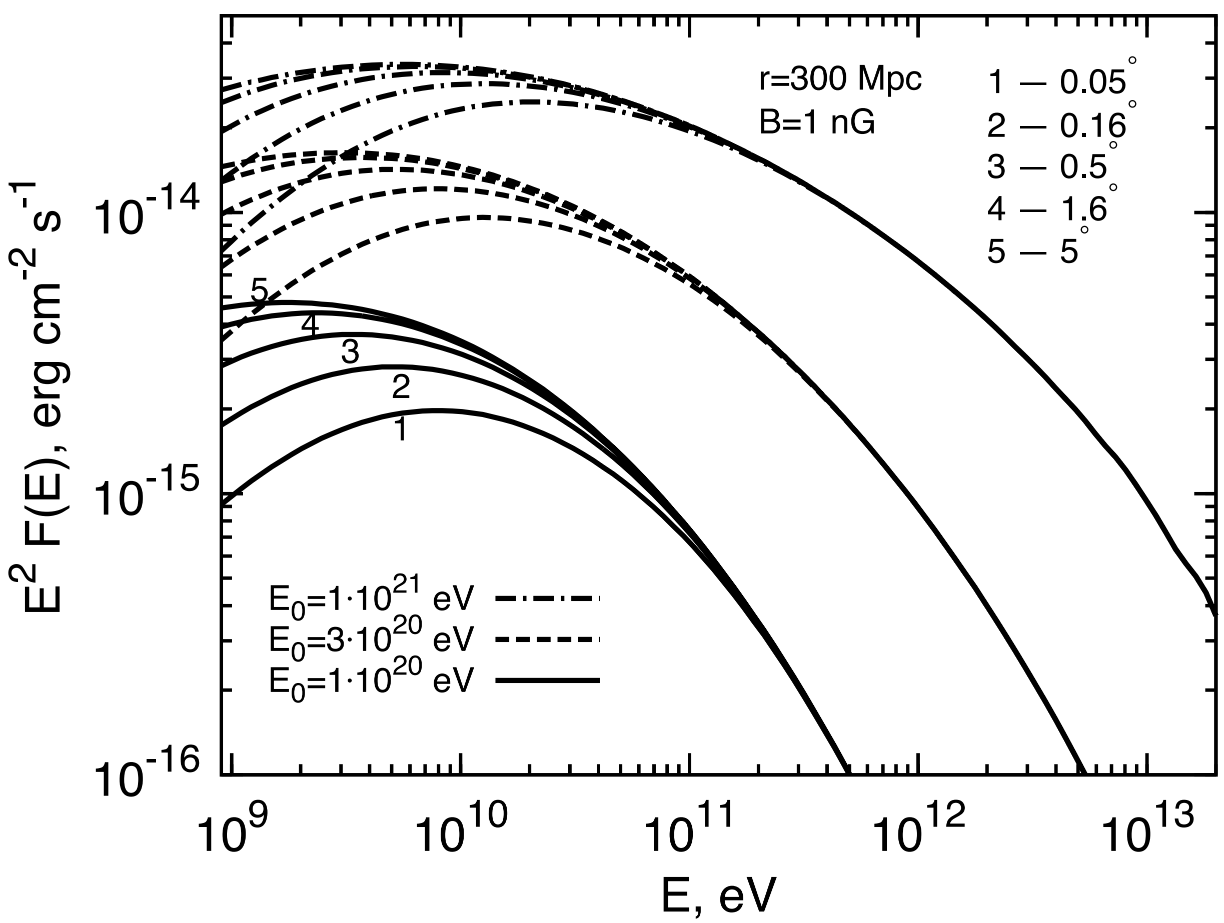
secondary electrons



Kelner&FA 2008

energy spectra of synchrotron radiation of secondary (pion-decay) electrons within different angles





$dN/dE = AE^{-\alpha} \exp(-E/E_o)$ with $\alpha=2$, $L_p=10^{44}$ erg/s; $B=1$nG; $\lambda=1$Mpc

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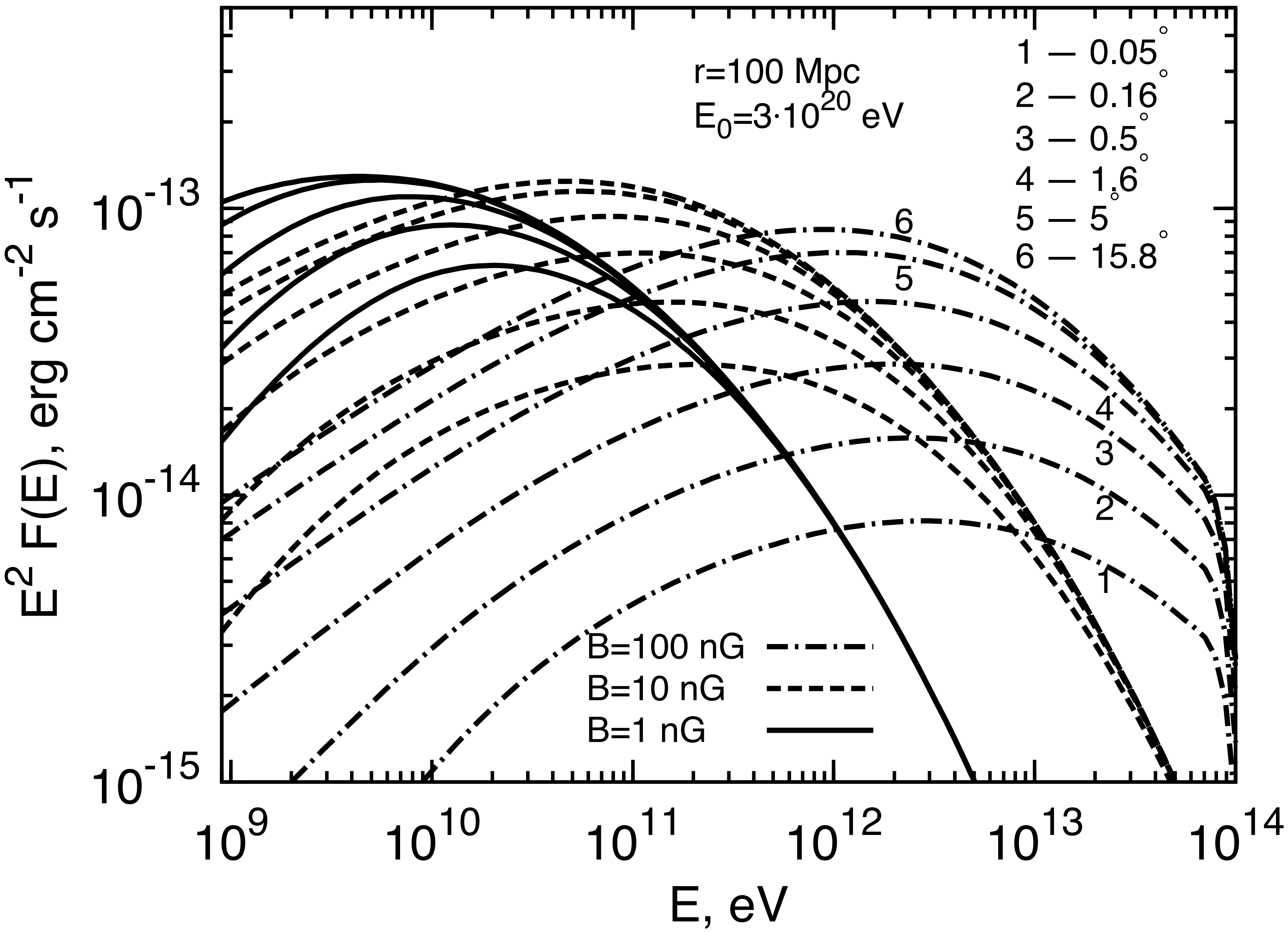
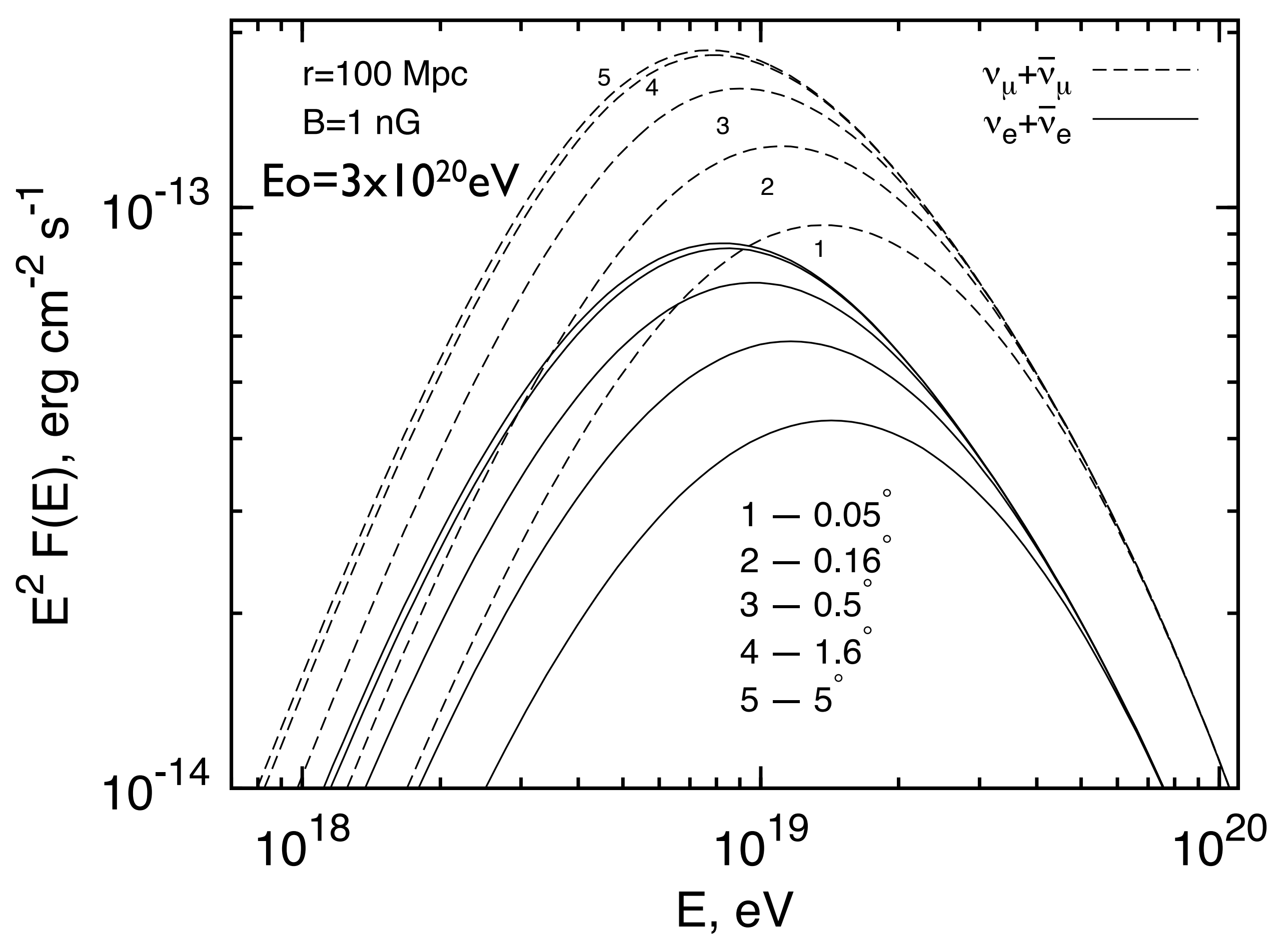
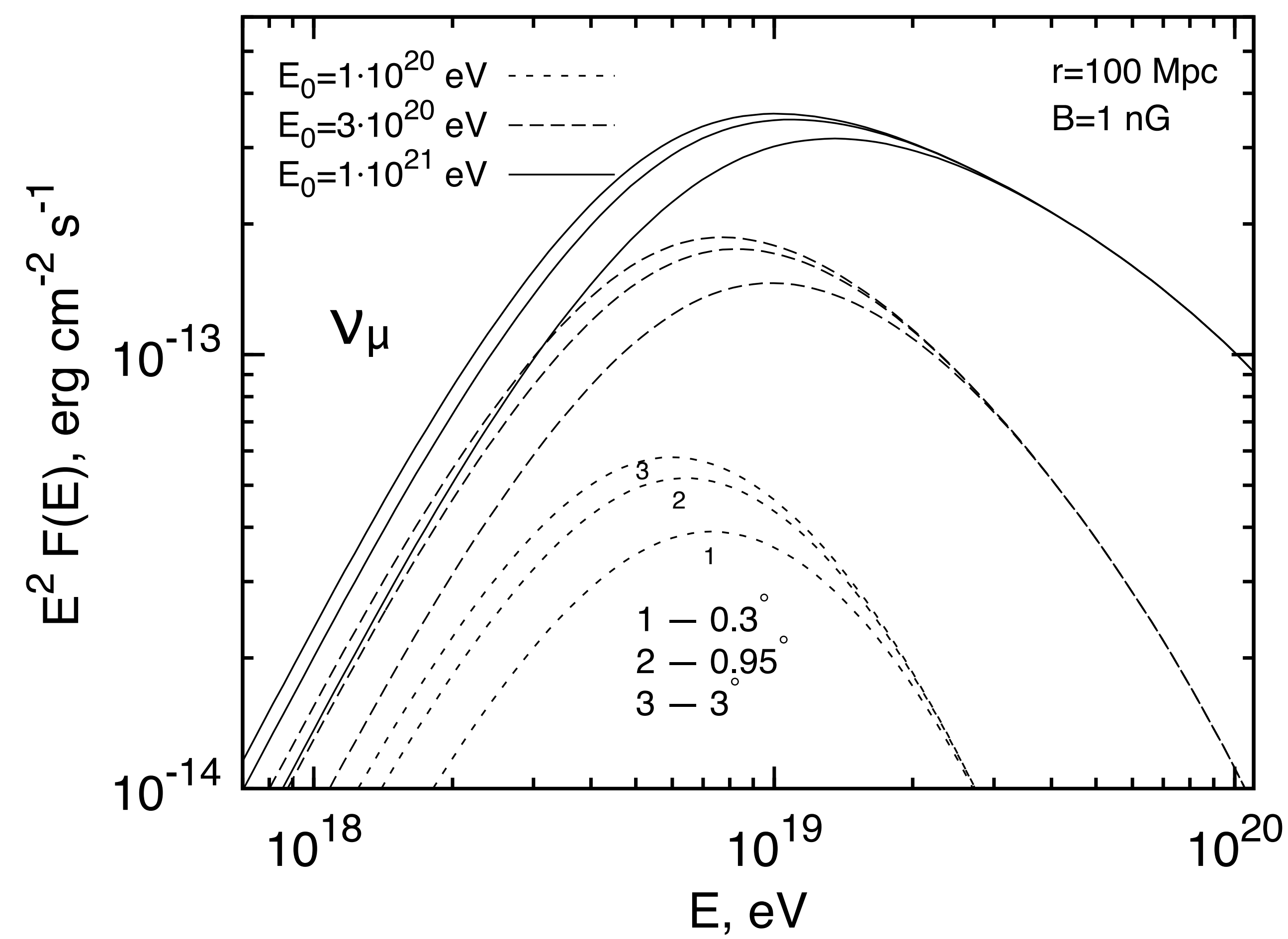


$dN/dE=AE^{-\alpha}\exp(-E/E_o)$ with $\alpha=2$, $E_o=3\times10^{20}$ eV; $L_p=10^{44}$ erg/s

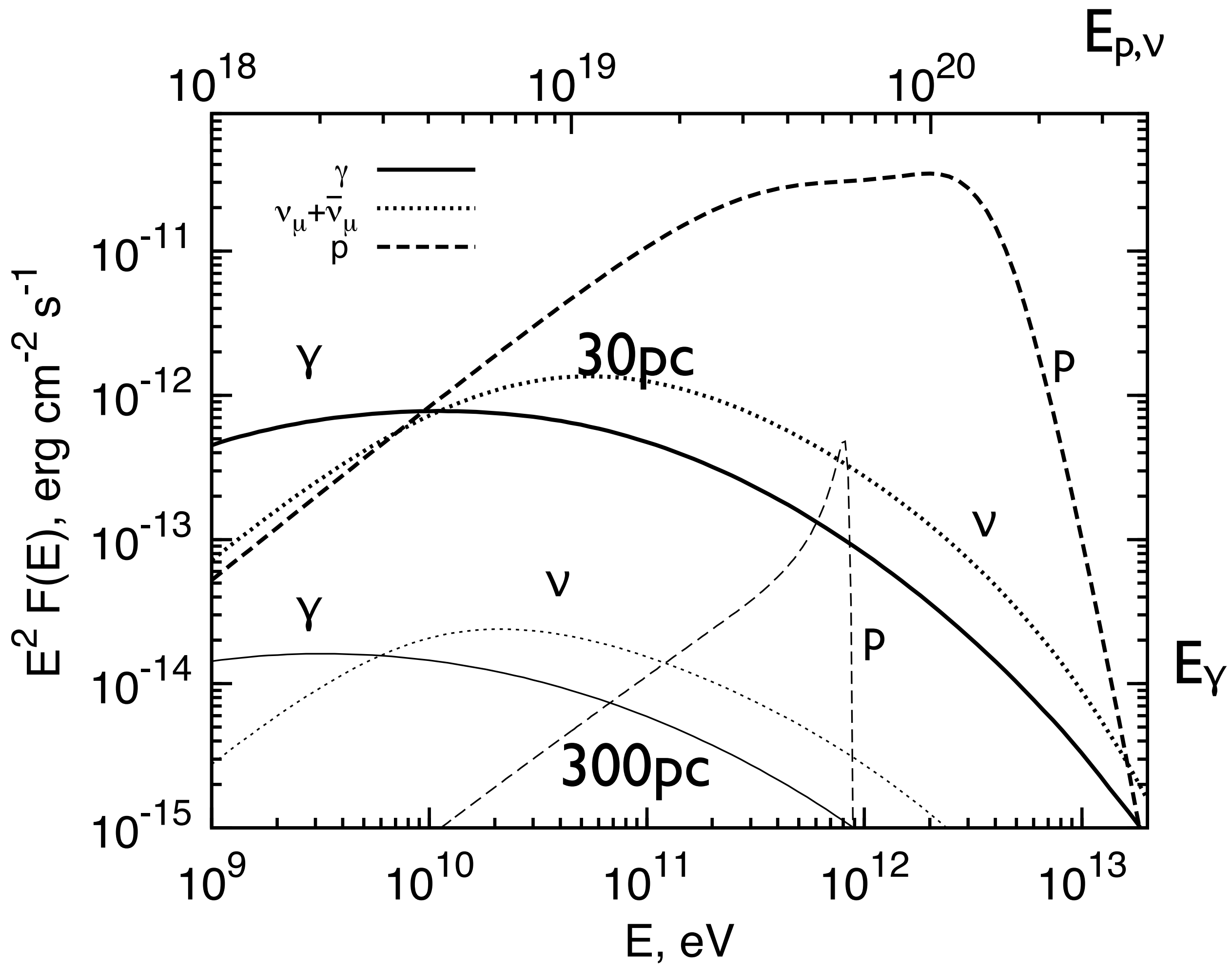
neutrinos



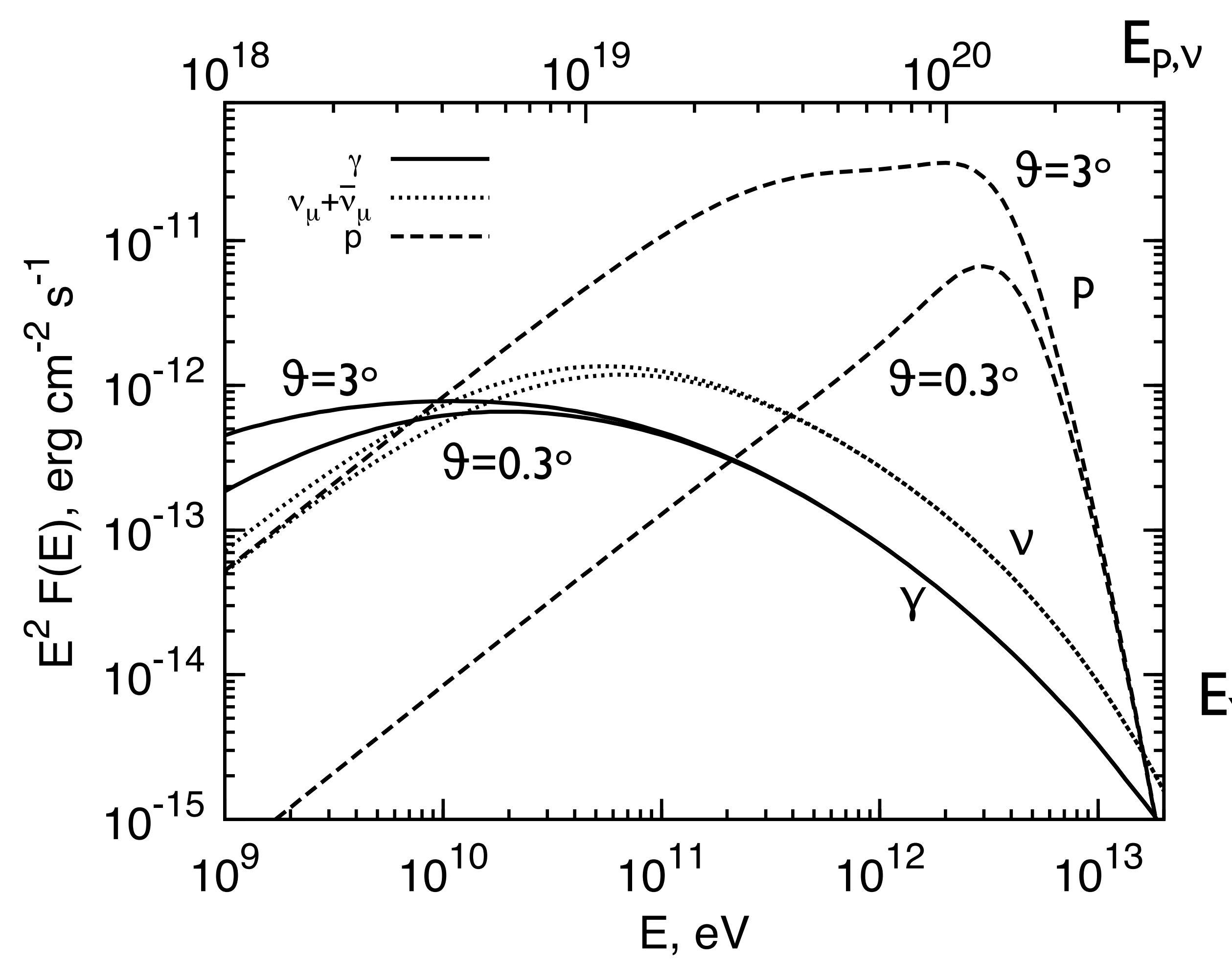


$dN/dE=AE^{-\alpha}\exp(-E/E_o)$ with $\alpha=2$, $L_p=10^{44}$ erg/s; B=1nG spectral energy distribution of gamma rays, muon neutrinos and protons*

$dN/dE = AE^{-\alpha}\exp(-E/E_o)$ with $\alpha=2$, $Eo=3\times10^{20}$ eV; $L_p=10^{44}$ erg/s; B=1nG



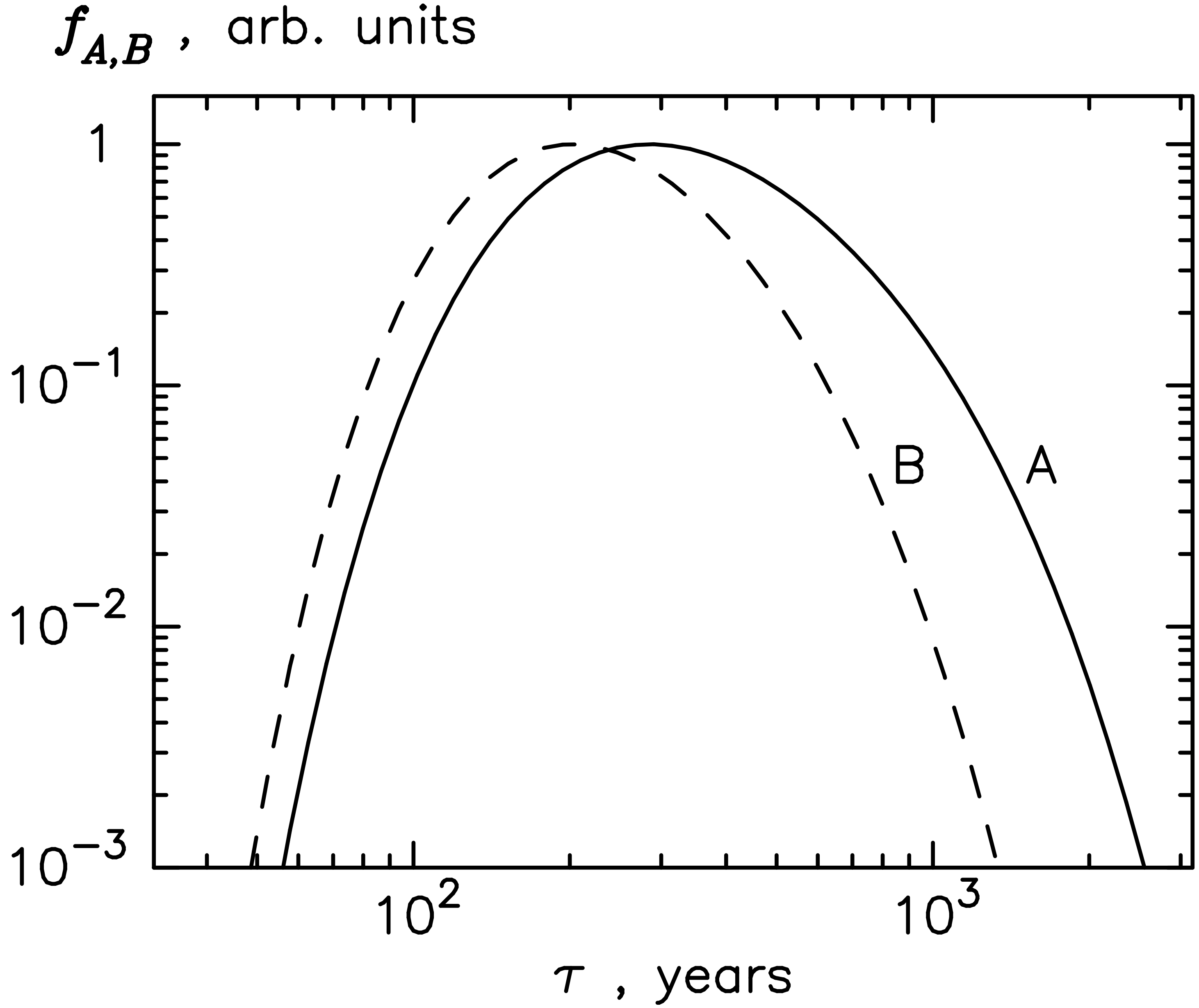
ϑ=3°



30Mpc

- ✓ if protons escape the source within a small angle towards the observer $\delta\Omega$, all fluxes are increased by a factor of $4\pi/\delta\Omega$
- ✓ if CR sources are located well beyond 100 Mpc - no chances to detect protons but synchrotron GeV-TeV γ-rays and EeV neutrinos can be yet observed

arrival time distribution of protons



A. detection of protons with arbitrary arrival angles;

B. protons arriving along the radius-vector at the regitration point

lg y = lg τ – 2 lg r – lg λ – 2 lgB + 2 lgE + const

$E=10^{20}$ eV; $L_p=10^{44}$ erg/s; B=1nG, d=10 Mpc