Standby

Intro. to Cosmos

Cosmos: http://cosmos.icrr.u-tokyo.ac.jp/

old one: https://cosmos.n.kanagawa-u.ac.jp/

UHECR air showers:

S. Roh *et al*., Astropart. Phys. 44 (2013) 1–8

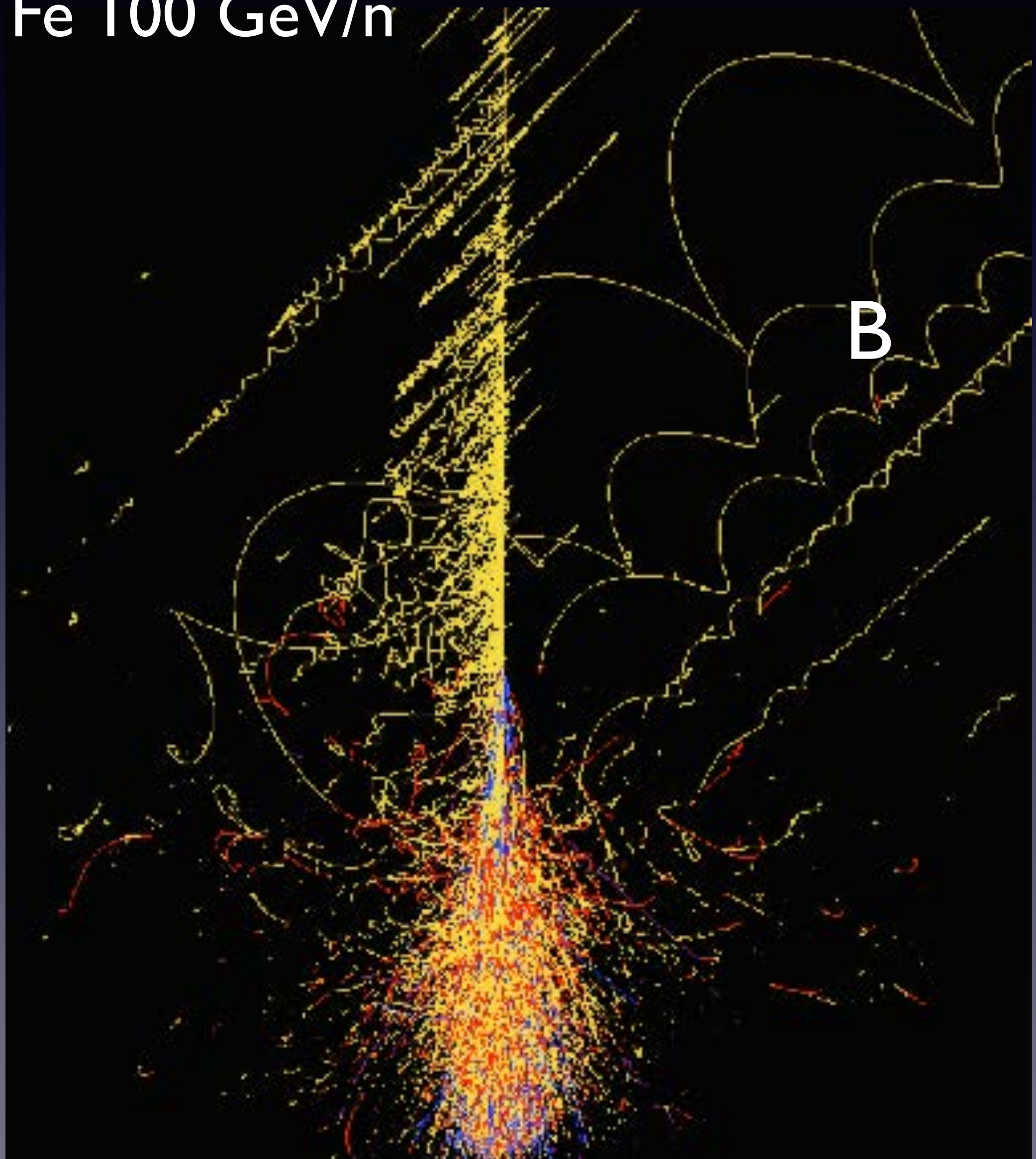
arXiv:1301.5060 [astro-ph.HE].

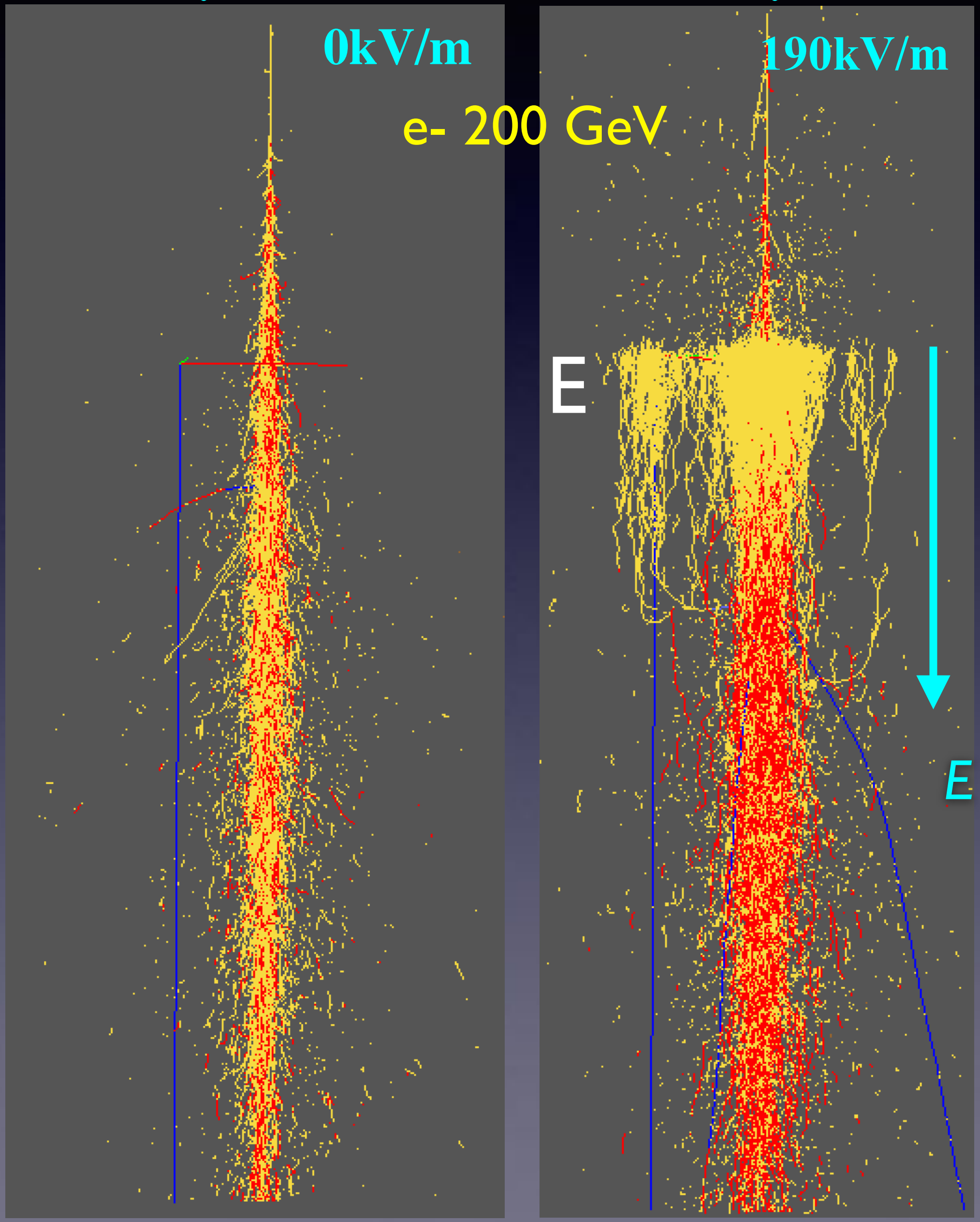
- Purpose, Physics processes involved
  - Electromagnetic interactions
  - Cascade theory/ Electric field
  - Hadronic interactions & related topics
- Program structure & user interface
- Current problems and future direction
  - Git/GitHub & Distributed system / collaborative development
    - http://git-scm.com/book/ja/

Air shower simulation

In the atmosphere

U.S standard Atmos. , NRL time-variable Atmos.



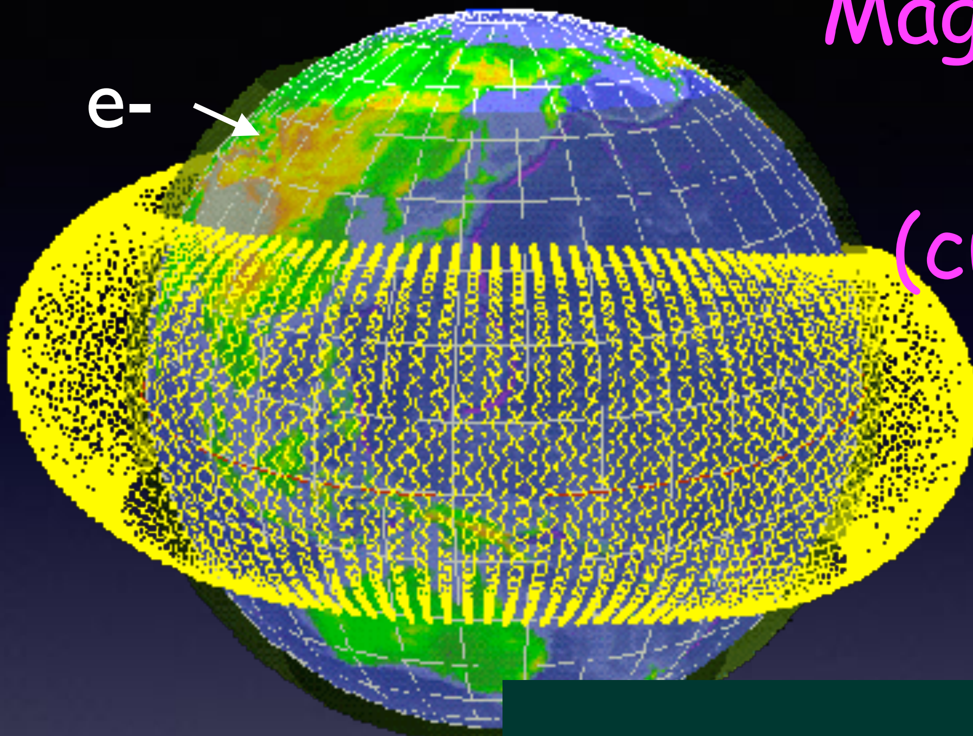


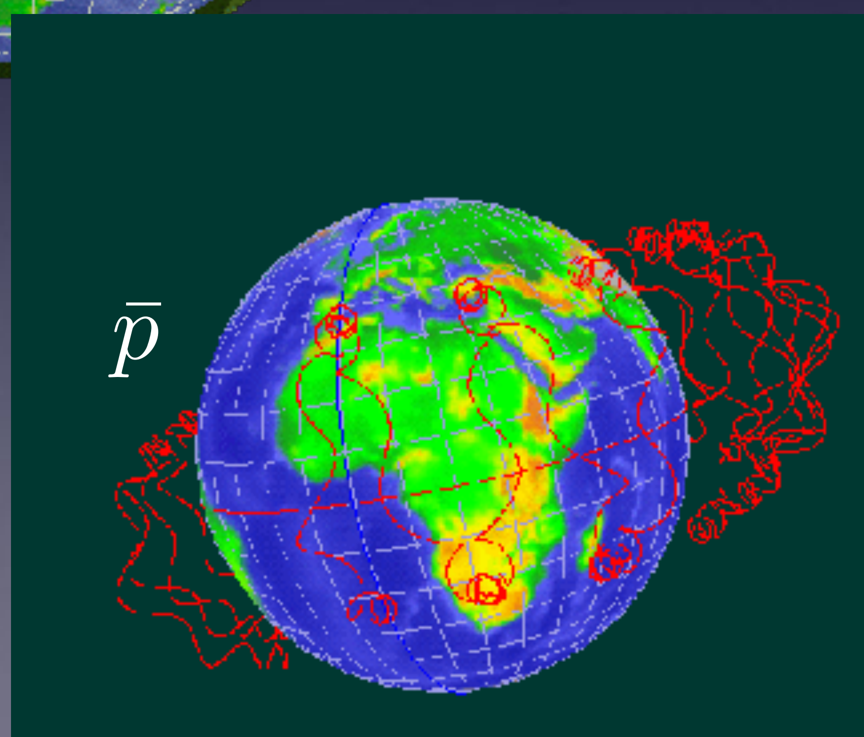
Near Earth Cosmic Ryas

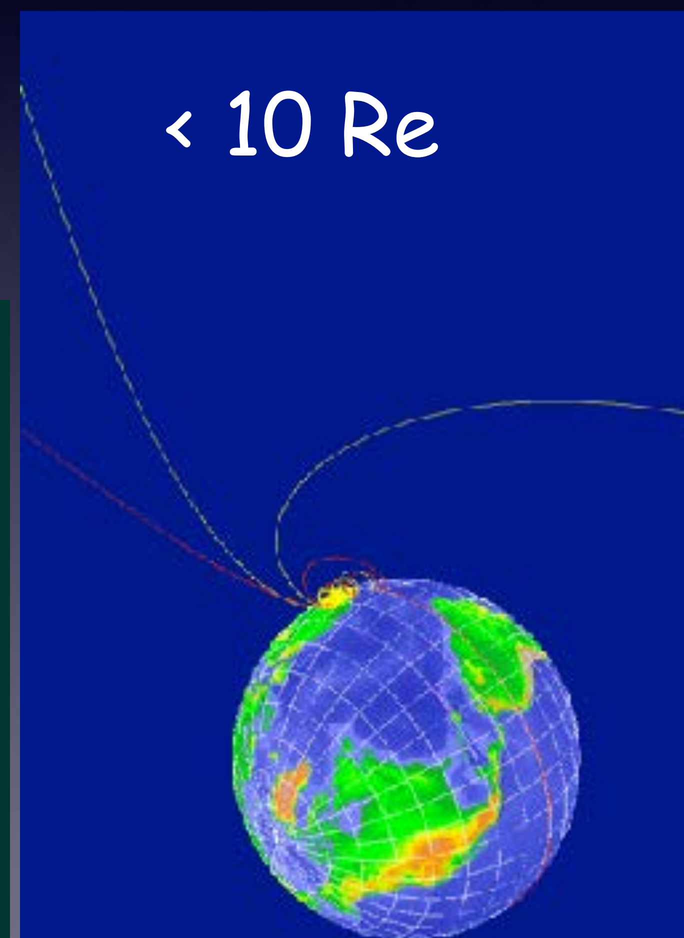
Mag. Field: IGRF 5 year step

WMM

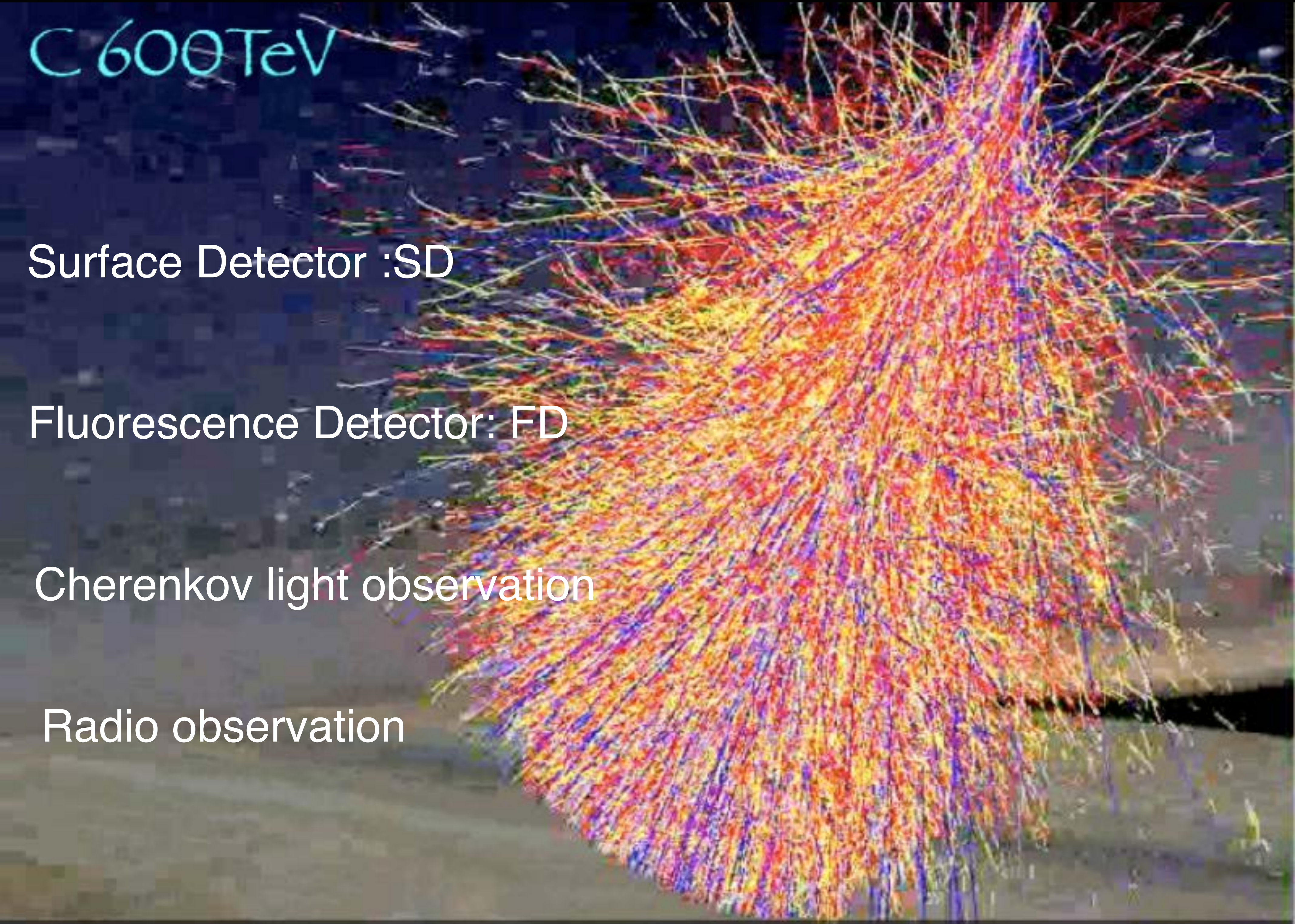
(customizable: e.g dipole B)







Air shower & its observation



Surface Detector :SD

Fluorescence Detector: FD

Cherenkov light observation

Radio observation

Energy Region & Particles

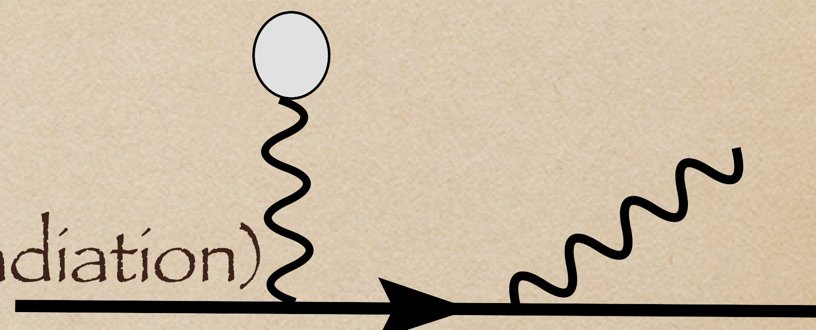
- 1keV ~ 10^{21} eV
  - model dependent
- Nucleus, p, n, d, t, photon, e, pi, K, mu, nu, resonances, D, .. light
- no nu interaction
  - no tau, nu-tau
  - model dependent

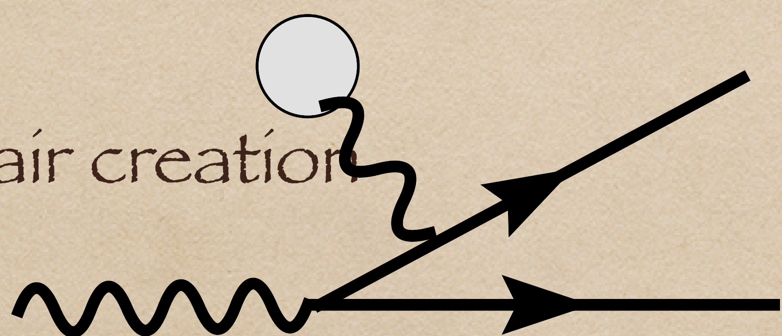
Processes

- ☑ Elemag:
  - ☑ photoelectric Eff., Rayleigh scat, Compton scat,
  - ☑ pair cre. mag. pair cre.
  - ☑ brems. e+ annihilation, Bhabha, Møller scat.
  - ☑ mag. brems (synchrotron rad).
  - ☑ photo-hadron prod.
- ☑ muon brems, pair cre. nucl. int.
- ☑ hadron interaction.
- ☑ ionization loss. knock on.
- ☑ multiple scatt.
- ☑ Landau Pomeranchuk eff. on pair/brems.
- ☑ Motion in E & B field
- ☑ Direct Pair creation(UPC)
- ☐ Cherenkov→some user interface

Electro-magnetic interactions

- Most important ones:
  - Bremsstrahlung(radiation)





  - Pair creation
  - Compton scattering

Cross-sections

$$C = Z\pi r_e^2 \frac{N_0}{A} (= 0.15 \frac{\mathrm{Z}}{\mathrm{A}} \mathrm{cm}^2/\mathrm{g})$$

Area covered by electrons in 1 g

E.G, Compton scattering

$$\sim C \frac{m_e}{E} (\ln(E/m_e) \ldots)(/\mathrm{g} \cdot \mathrm{cm}^{-2})$$

Radiation length (pair, brems)

$$\frac{1}{X_0} = 4\alpha r_e^2 \frac{N_0}{A} Z(Z+1)(\ln Z \ldots)$$

~ 3Z^2 mb

$$X_0 \propto \frac{A}{Z(Z+1)} \propto \frac{1}{Z}$$

very roughly !

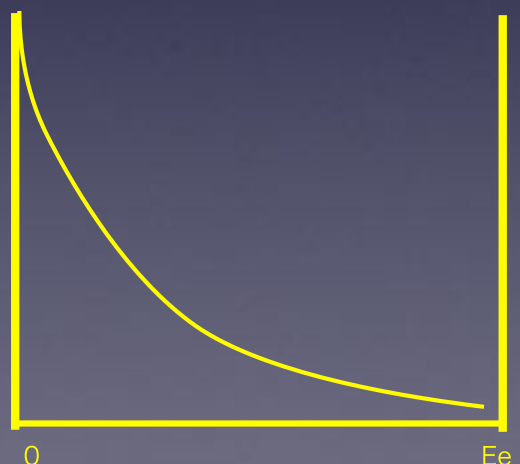
$$X_0(\mathrm{air}) = 36.6(\mathrm{g/cm}^2) \sim 300 \text{ m (at sea level)}$$

$$X_0(\mathrm{Pb}) = 0.56\mathrm{cm}$$

$$\mathrm{Paircreation}/X_0 : \varphi(E')dE' \sim \frac{dE'}{E_\gamma}\frac{1}{\frac{9}{7}}$$

E'(Energy of e^+ or e^-)

$$\mathrm{Bremsstralung}/X_0 : \varphi(E')dE' \sim \frac{dE'}{E'}$$



E'(Energy of γ)

$v(= E_\gamma/E_e)$

- Brems:
  - Seltzer & Berger (numerical data) 1keV~10GeV

    S.M.Seltzer and M.J.Berger. Nucl.Inst.Meth. 80 (1985) 12.
  - Tsai

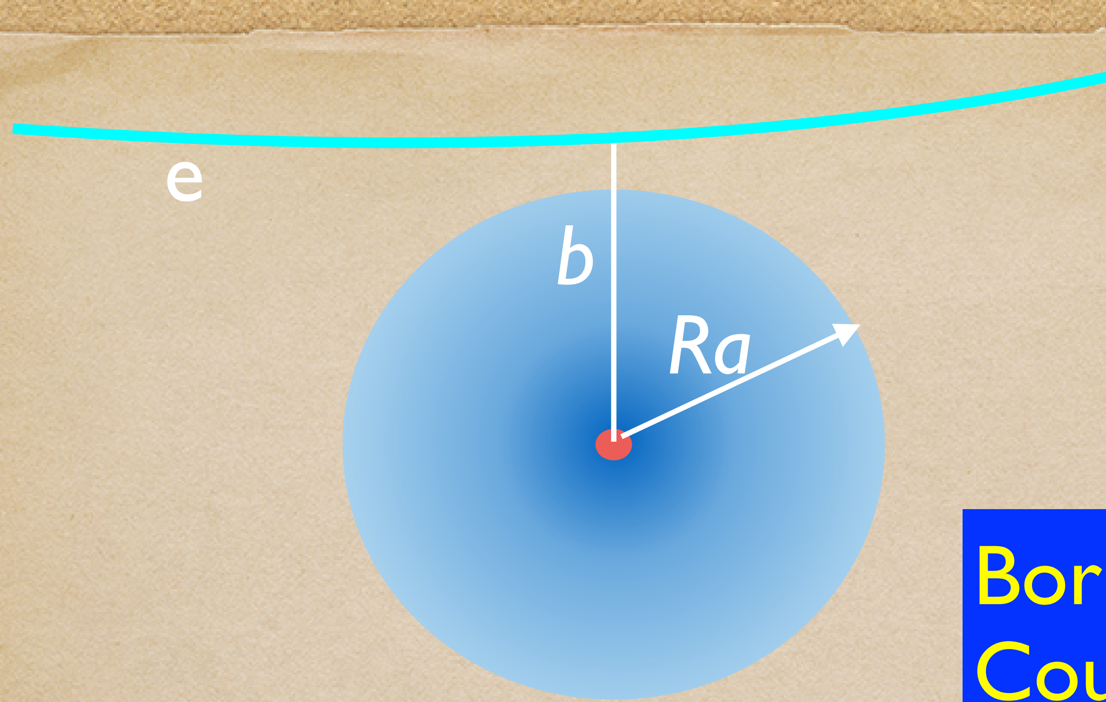
    Y-S . Tsai . Rev. Mod. Phys. 49. (1977) 42
  - Messel & Crawford modified by Koch & Motz

    Rev.Mod.Phys.Vol.31,No.4 1959
  - Migdal LPM

    A.B. Migdal, Phys. Rev. 103 (1956) 1811.
- Pair
  - XCOM (numerical data v3.1): 1keV~100GeV

    Berger, Seltzer,& Hubbel, http://physics.nist.gov/XCOM
  - Nelson

    W.R. Nelson et al.: EGS4,SLAC-Report-265 , December 1985
  - Messel & Crawford modified by Koch & Motz
  - Migdal LPM



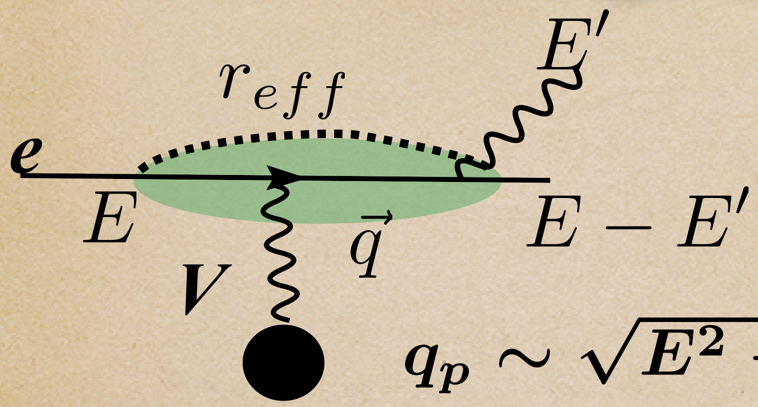
effective b > Ra
nucleus point charge
Atom:
model. Thomas-Fermi
screening treatment

Born approx.
Coulomb correc. $(\alpha Z)^2$
Numerical computation
LPM

$$s = \frac{1}{\alpha\gamma}\frac{v}{1-v}\frac{1}{Z^{1/3}} \quad (v = E_\gamma/E_e)$$

s~0: complete screening
partial screening
s>>1: no screening

LPM Effect



$$q_p \sim \sqrt{E^2-m^2} - (\sqrt{(E-E')^2-m^2}+E')$$

For $E-E' \gg m$

$$q_p \sim \frac{m^2}{2}\frac{E'}{E(E-E')}$$

Effective interaction length $\quad r_{eff}q_p \sim 1$

$$r_{eff} \sim \frac{2E(E-E')}{mc^2E'}\frac{\hbar}{mc}$$

At high energies, r_{eff}, becomes larger than

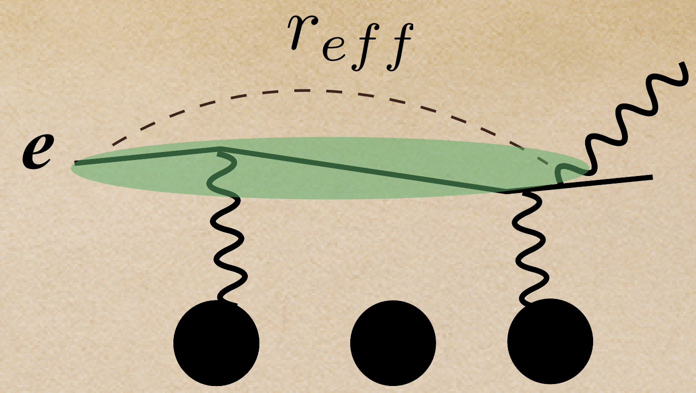
the atomic radius, $\frac{1}{\alpha}\frac{\hbar}{mc}\frac{1}{Z^{1/3}}$

Cross-section saturate $\Rightarrow$ complete screeing

However, in dense material

$$r_{eff} \sim \frac{2E(E-E')}{mc^2 E'} \frac{\hbar}{mc}$$

extends many atoms and suffers multiple scattering



If the multiple scattering angle, $<\theta> \sim \frac{E_s}{E}\sqrt{\frac{r_{eff}\rho}{X_0}}$
exceeds the brems angle, $\sim \frac{m}{E}$, $E_s \sim 20$ MeV (scattering const.)
negative interference takes place (Landau):

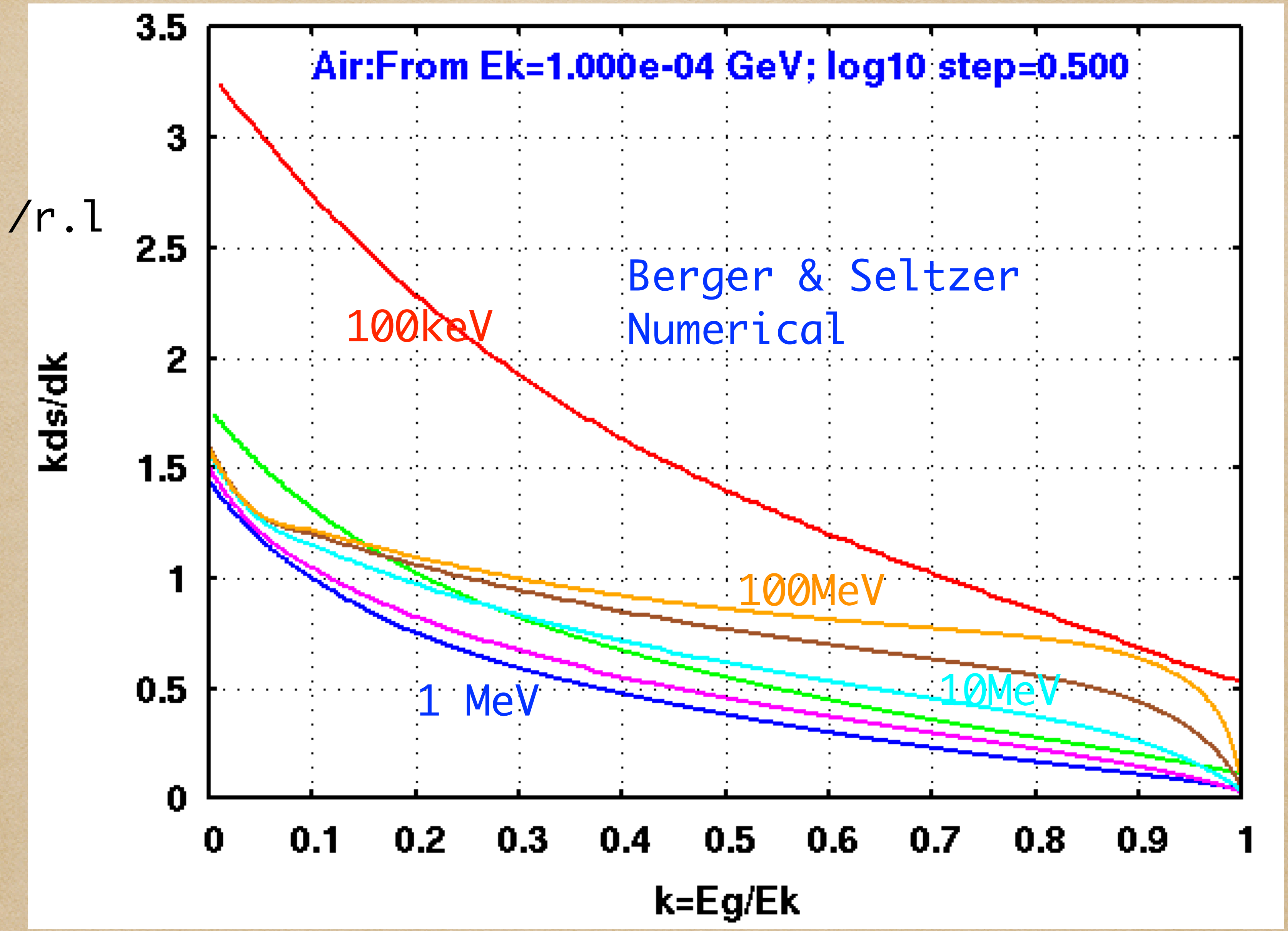
$<\theta> > m/E$ **leads to**

$$\frac{E(E-E')}{E'} \gtrsim 4 \times 10^{12} \frac{X_0}{\text{cm}} \text{eV}$$

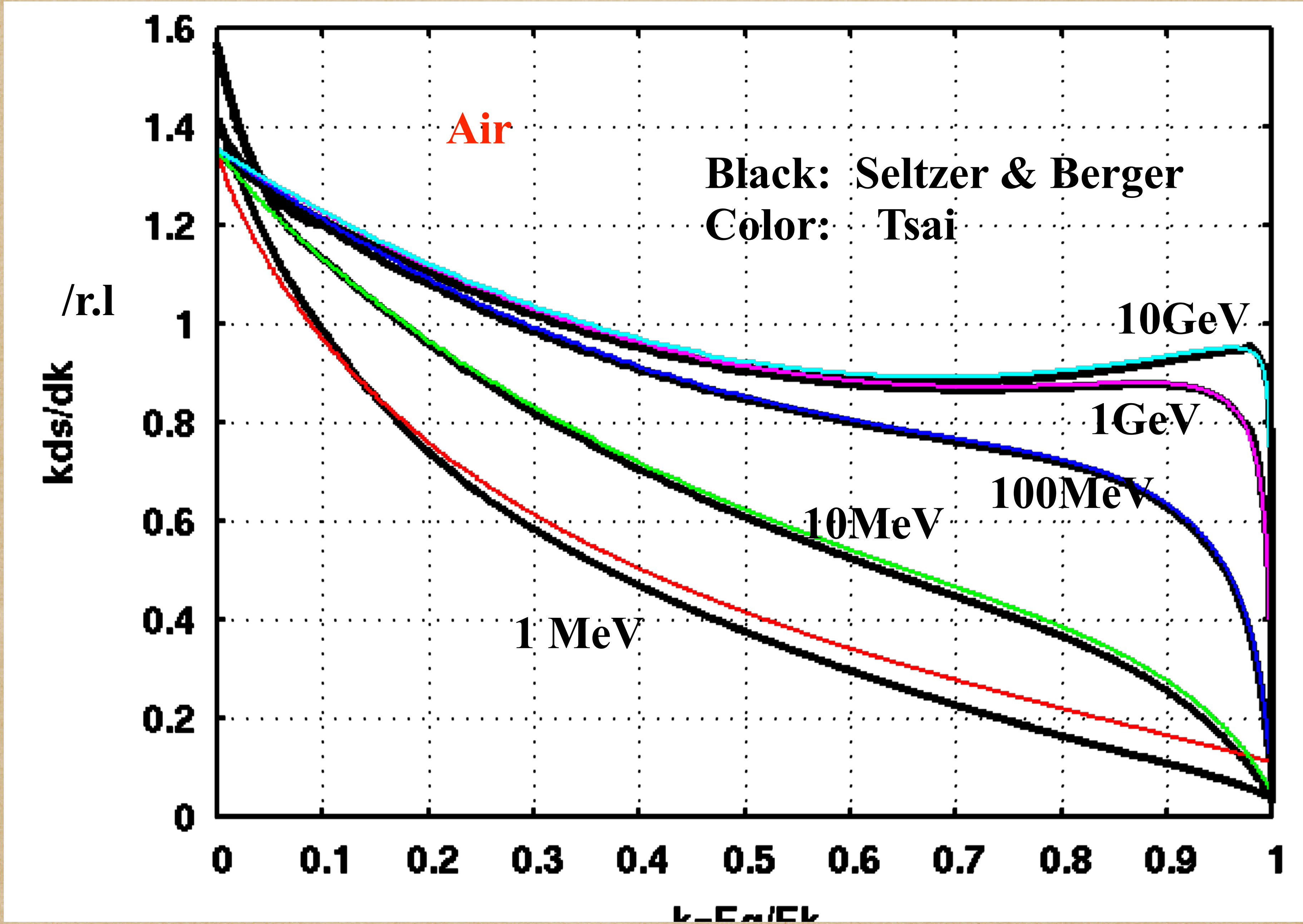
for $E' = E/2$, $E \sim 2 \times 10^{12}$ **eV (Pb);** $E \sim 10^{18}$ **eV (Upper Air)**

Midgal: $s = \frac{m}{2E<\theta>} = 10^6 \sqrt{\frac{E' X_0}{E(E-E)} \frac{\text{eV}}{\text{cm}}}$ $\quad s < 1 \rightarrow$ **LPM works**

- Brems:

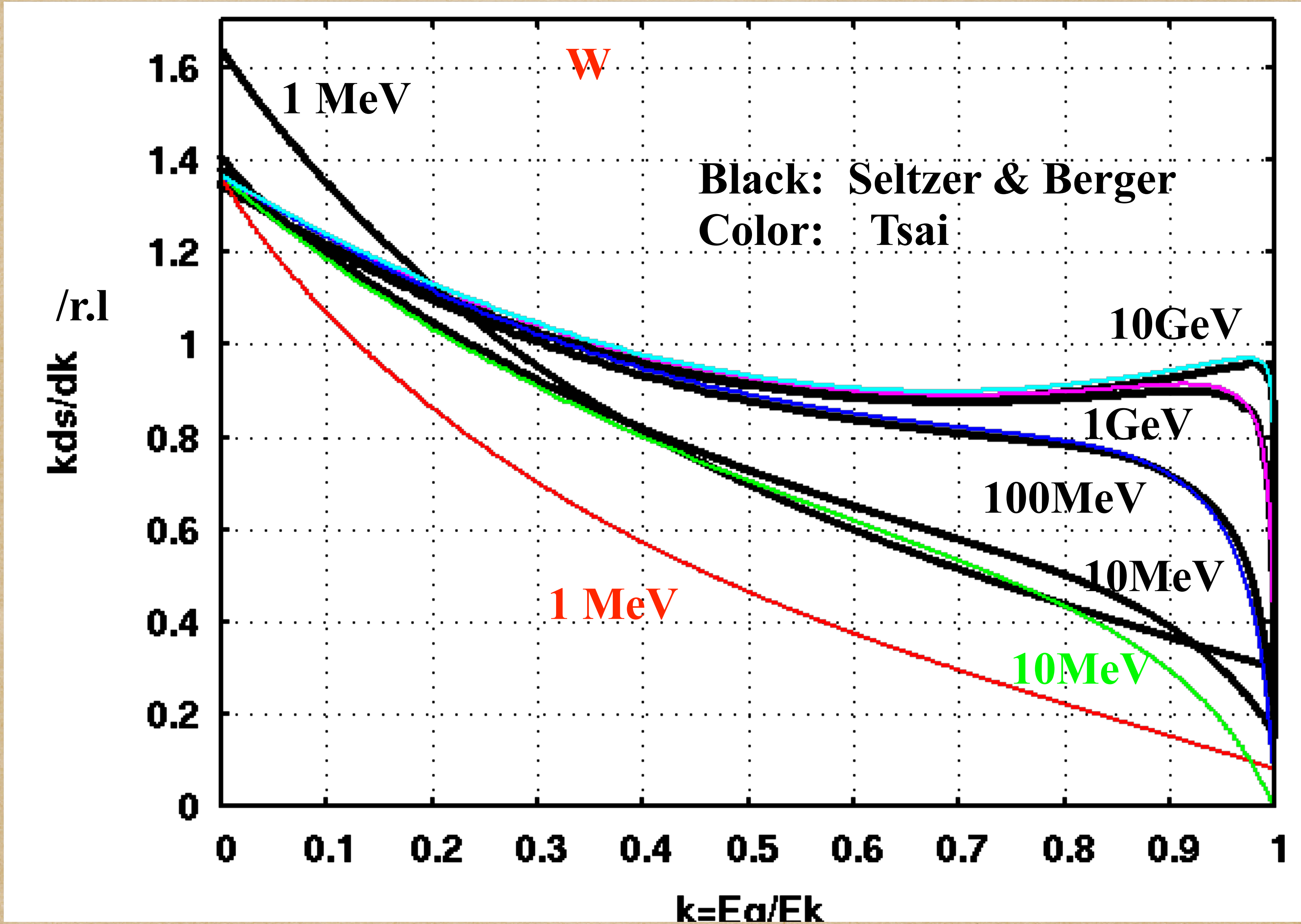

Air:From Ek=1.000e-04 GeV; log10 step=0.500
/r.l
kds/dk
3.5
3
2.5
2
1.5
1
0.5
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
k=Eg/Ek
Berger & Seltzer
Numerical
100keV
100MeV
10MeV
1 MeV

- Brems:



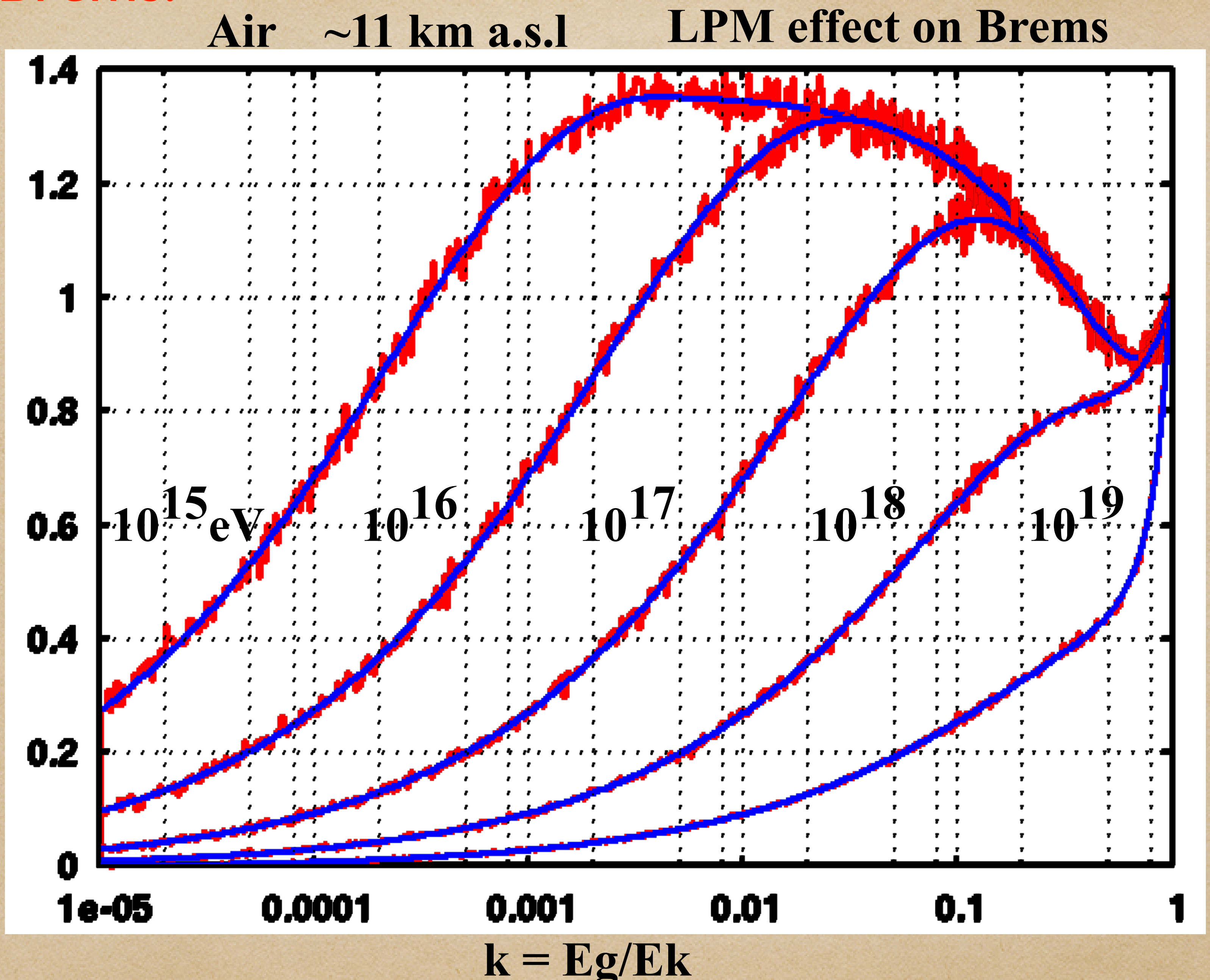
Air
Black: Seltzer & Berger
Color: Tsai
/r.l
kds/dk
10GeV
1GeV
100MeV
10MeV
1 MeV
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

- Brems:



W
1 MeV
Black: Seltzer & Berger
Color: Tsai
10GeV
1GeV
100MeV
10MeV
1 MeV
10MeV
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
kds/dk /r.l
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
k=Eg/Ek

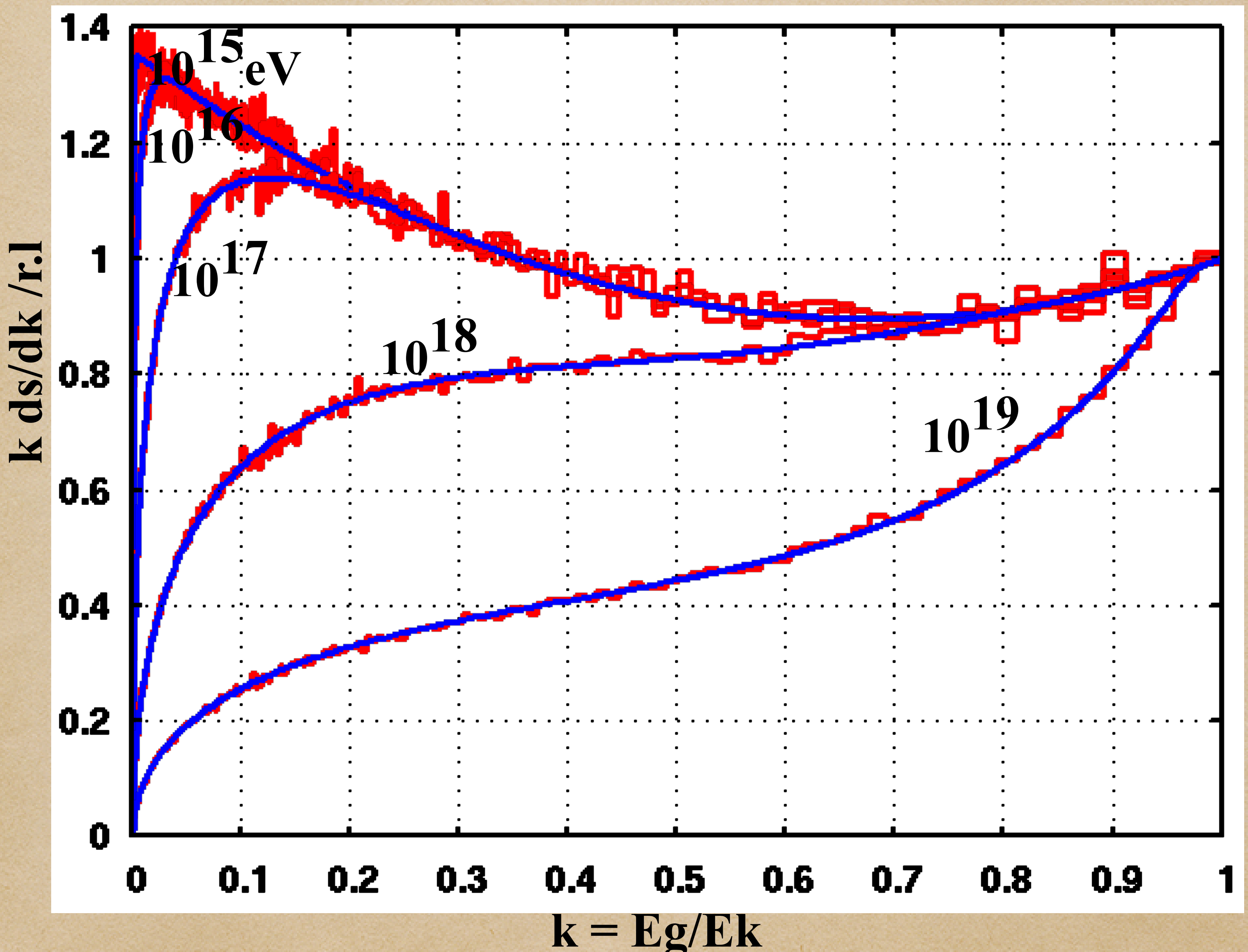
- Brems:



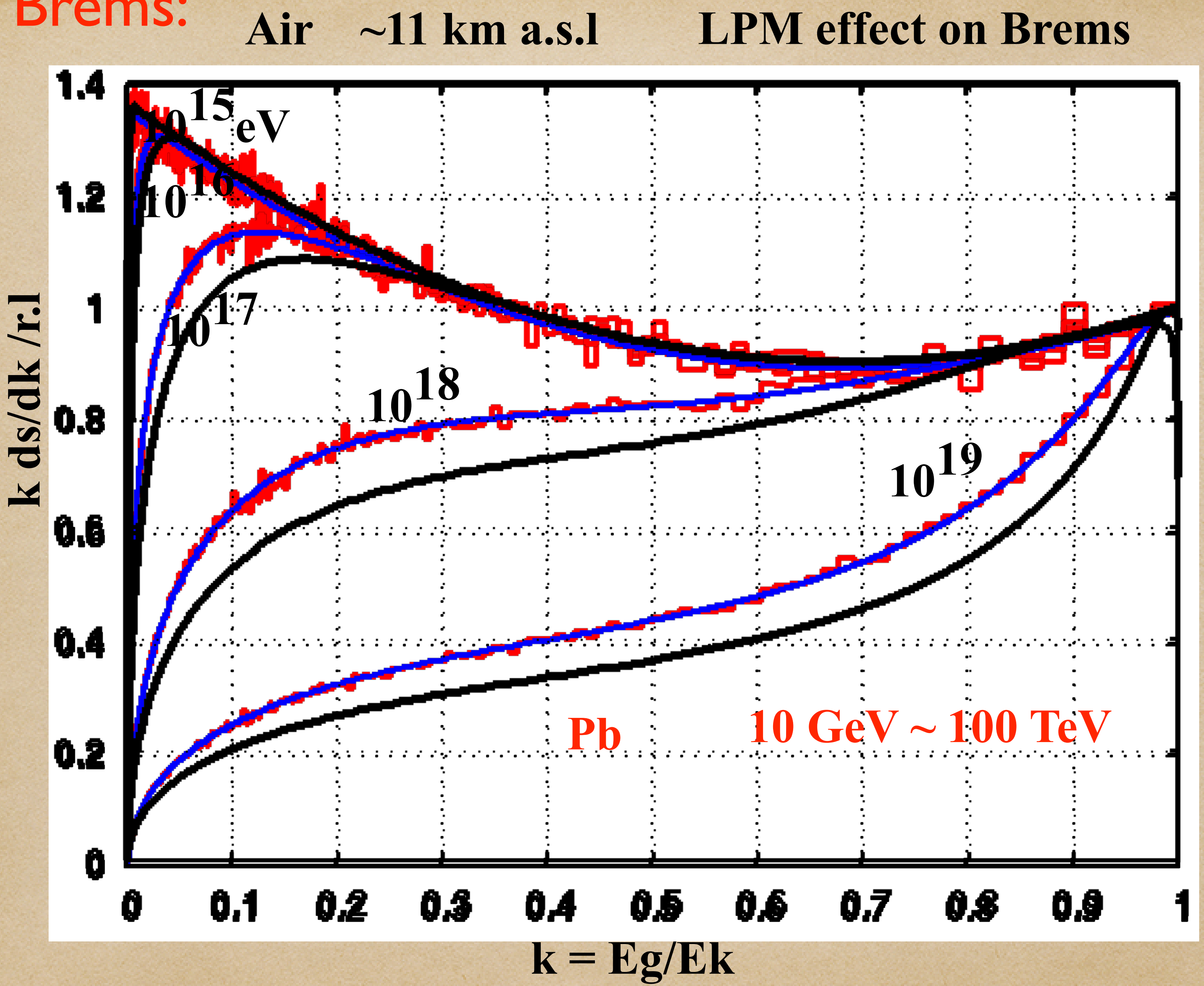
Air ~11 km a.s.l
LPM effect on Brems
k ds/dk /r.l
k = Eg/Ek
10^15 eV
10^16
10^17
10^18
10^19
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1e-05
0.0001
0.001
0.01
0.1
1

- Brems:

Air ~11 km a.s.l LPM effect on Brems

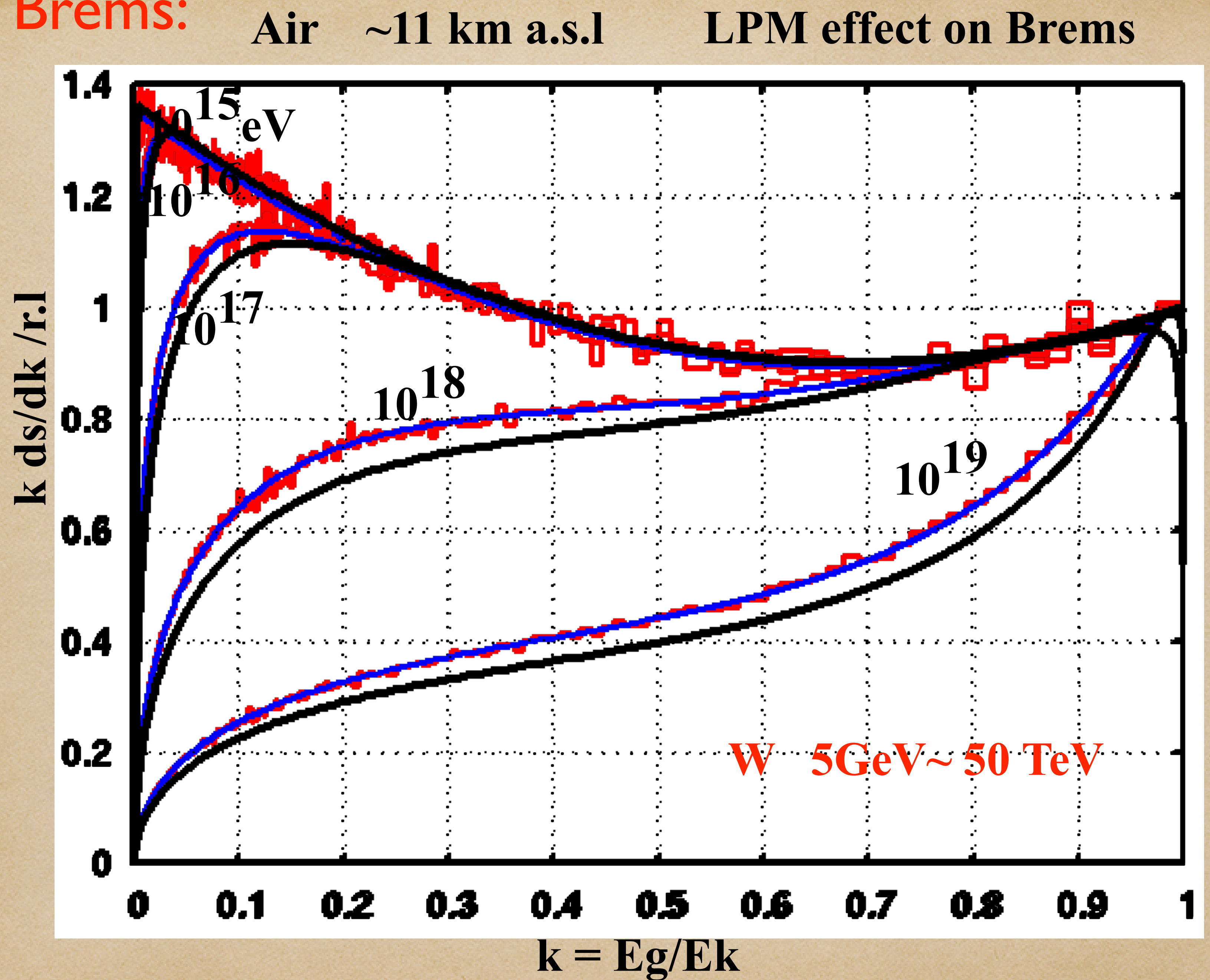


- Brems:



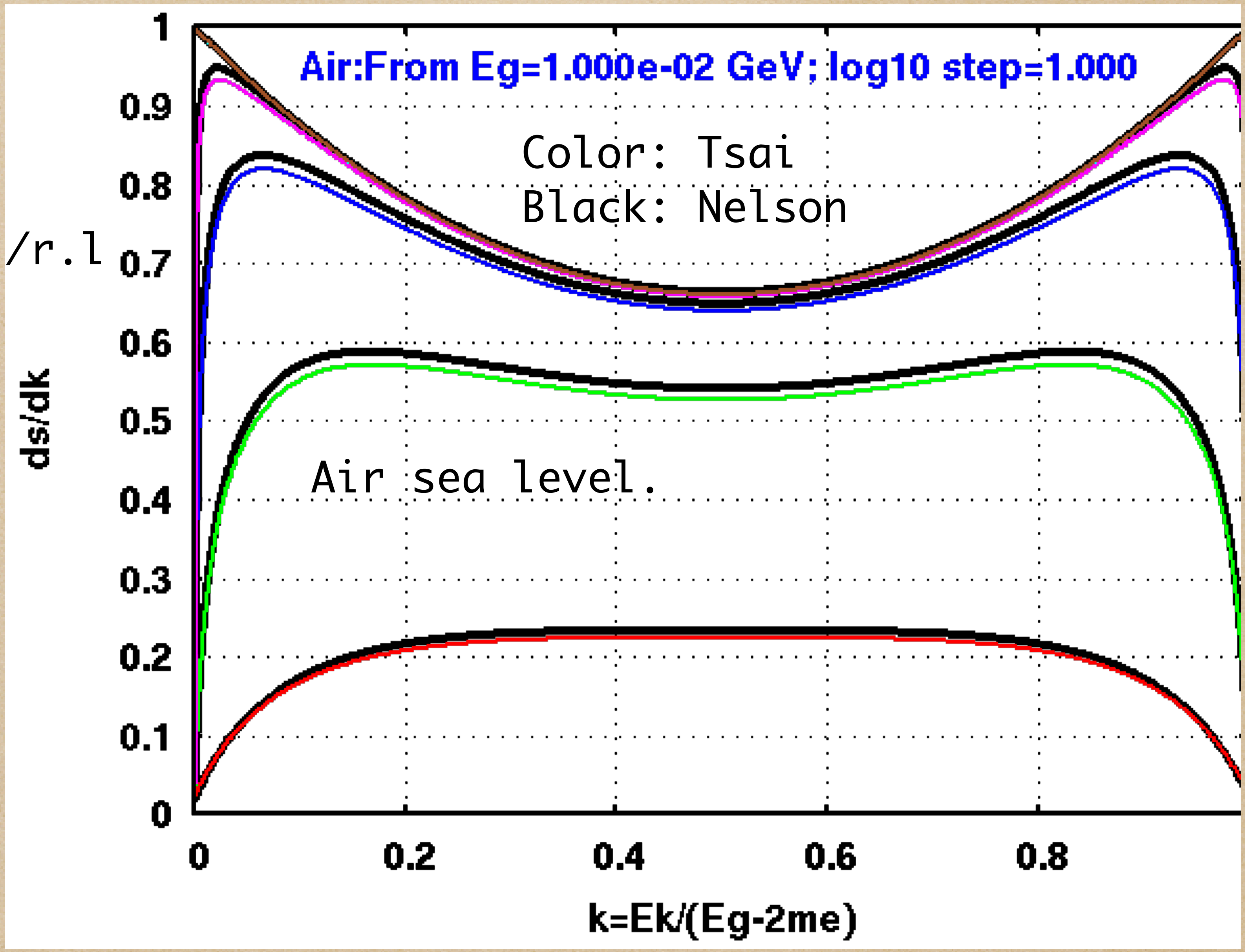
Air ~11 km a.s.l
LPM effect on Brems
k ds/dk /r.l
k = Eg/Ek
10^15 eV
10^16
10^17
10^18
10^19
Pb
10 GeV ~ 100 TeV
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

- Brems:



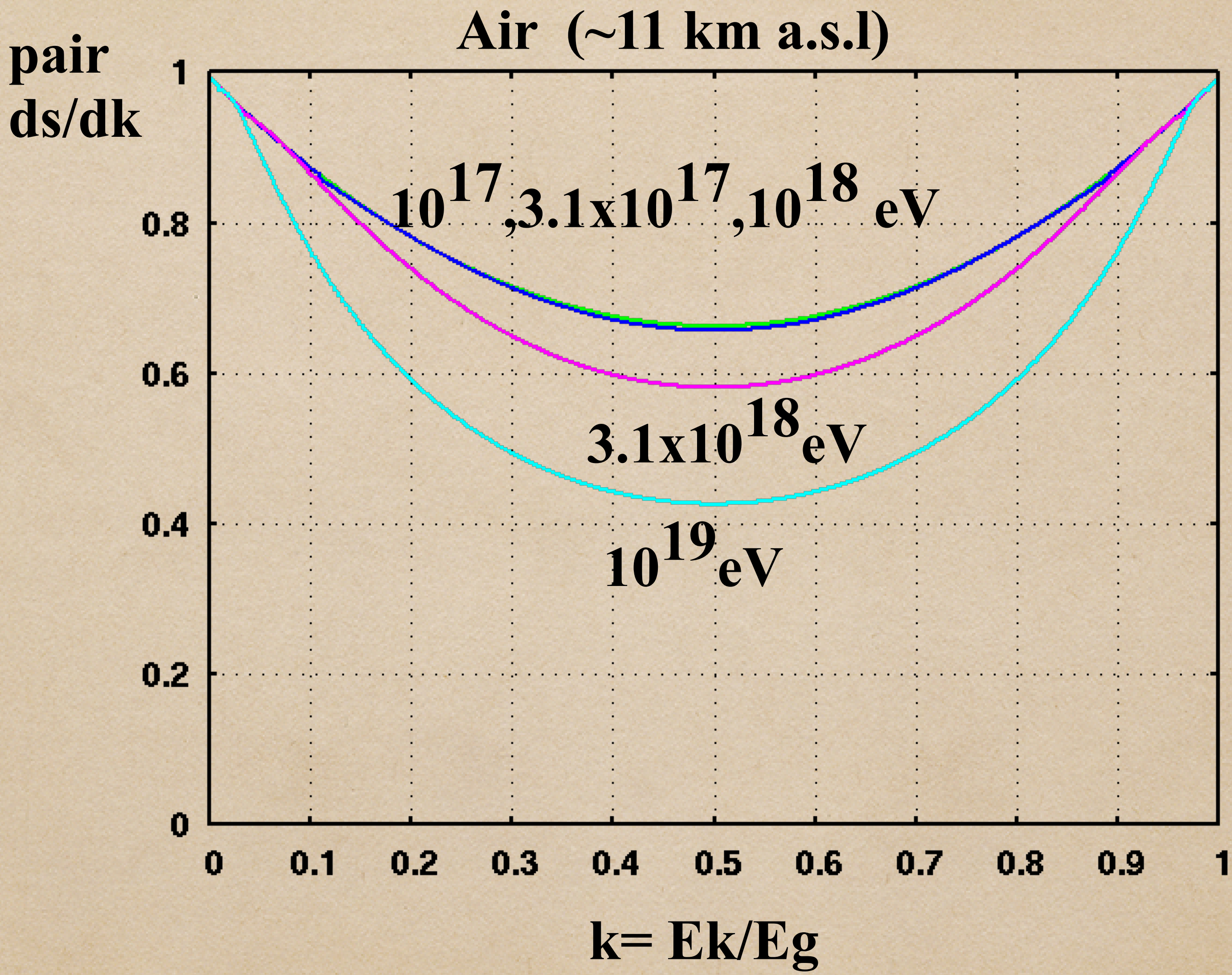
Air ~11 km a.s.l
LPM effect on Brems
10^{15}eV
10^{16}
10^{17}
10^{18}
10^{19}
W 5GeV~ 50 TeV
k ds/dk /r.l
k = Eg/Ek
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

- Pair:



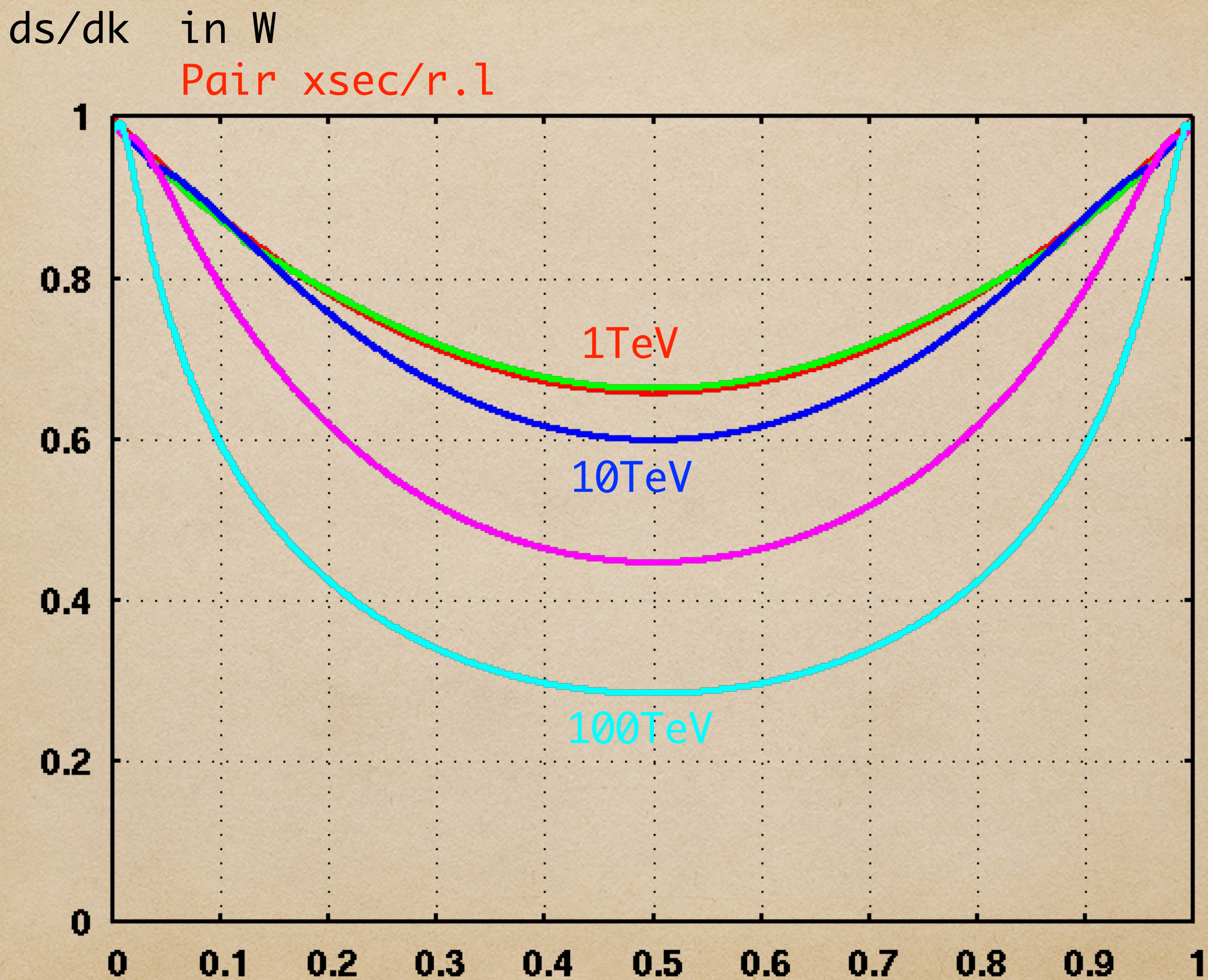
Air:From Eg=1.000e-02 GeV; log10 step=1.000
Color: Tsai
Black: Nelson
Air sea level.
ds/dk
/r.l
k=Ek/(Eg-2me)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.2
0.4
0.6
0.8

- Pair:

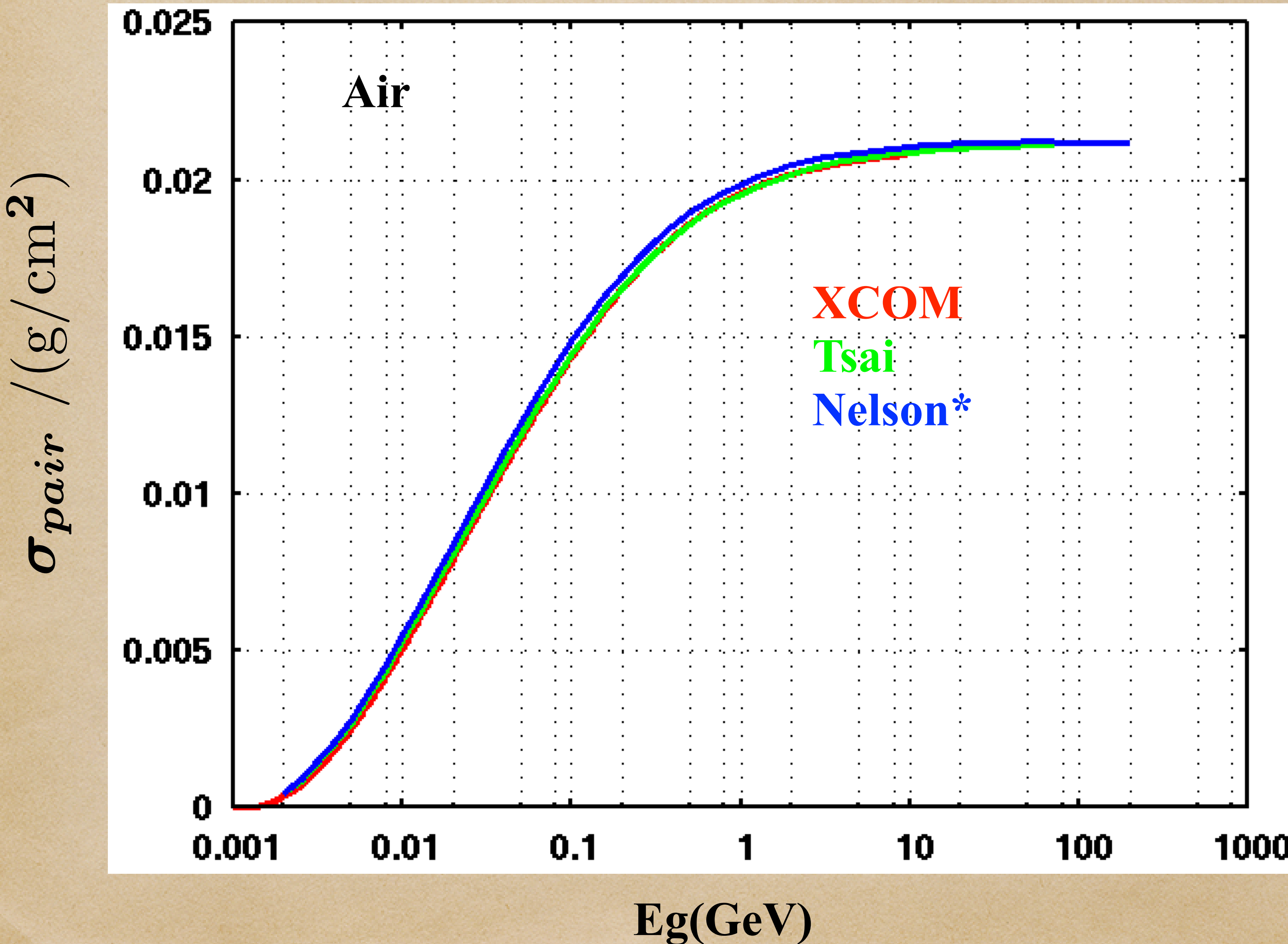


Air (~11 km a.s.l)
pair
ds/dk
1
0.8
0.6
0.4
0.2
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
10^17,3.1x10^17,10^18 eV
3.1x10^18 eV
10^19 eV
k= Ek/Eg

- Pair:

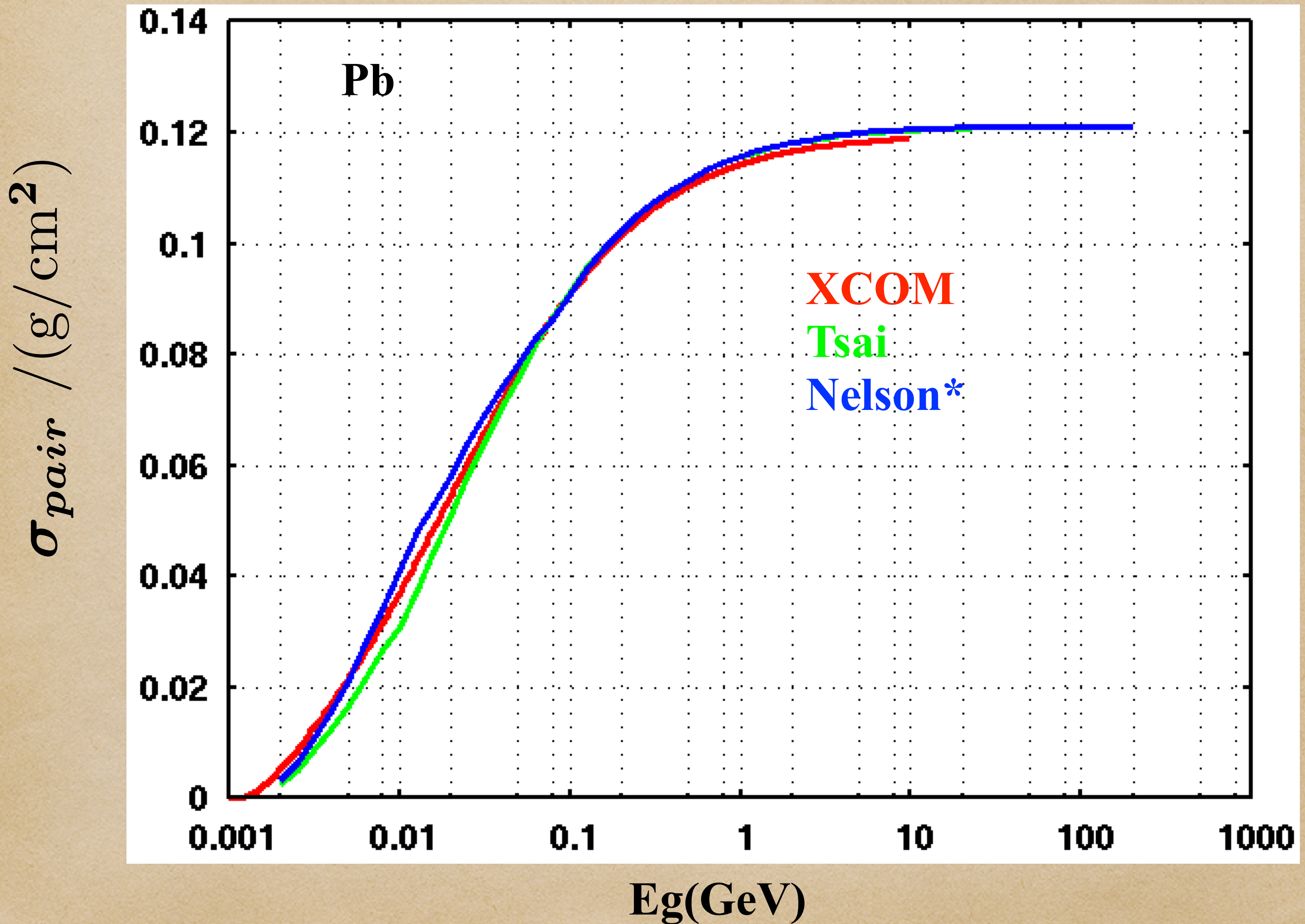

ds/dk in W
Pair xsec/r.l
1
0.8
0.6
0.4
0.2
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1TeV
10TeV
100TeV

- Pair:



Air
XCOM
Tsai
Nelson*
0.025
0.02
0.015
0.01
0.005
0
0.001
0.01
0.1
1
10
100
1000
σ_{pair} /(g/cm^2)
Eg(GeV)

- Pair:


Pb
XCOM
Tsai
Nelson*
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0.001
0.01
0.1
1
10
100
1000
σ_{pair} /(g/cm^2)
Eg(GeV)

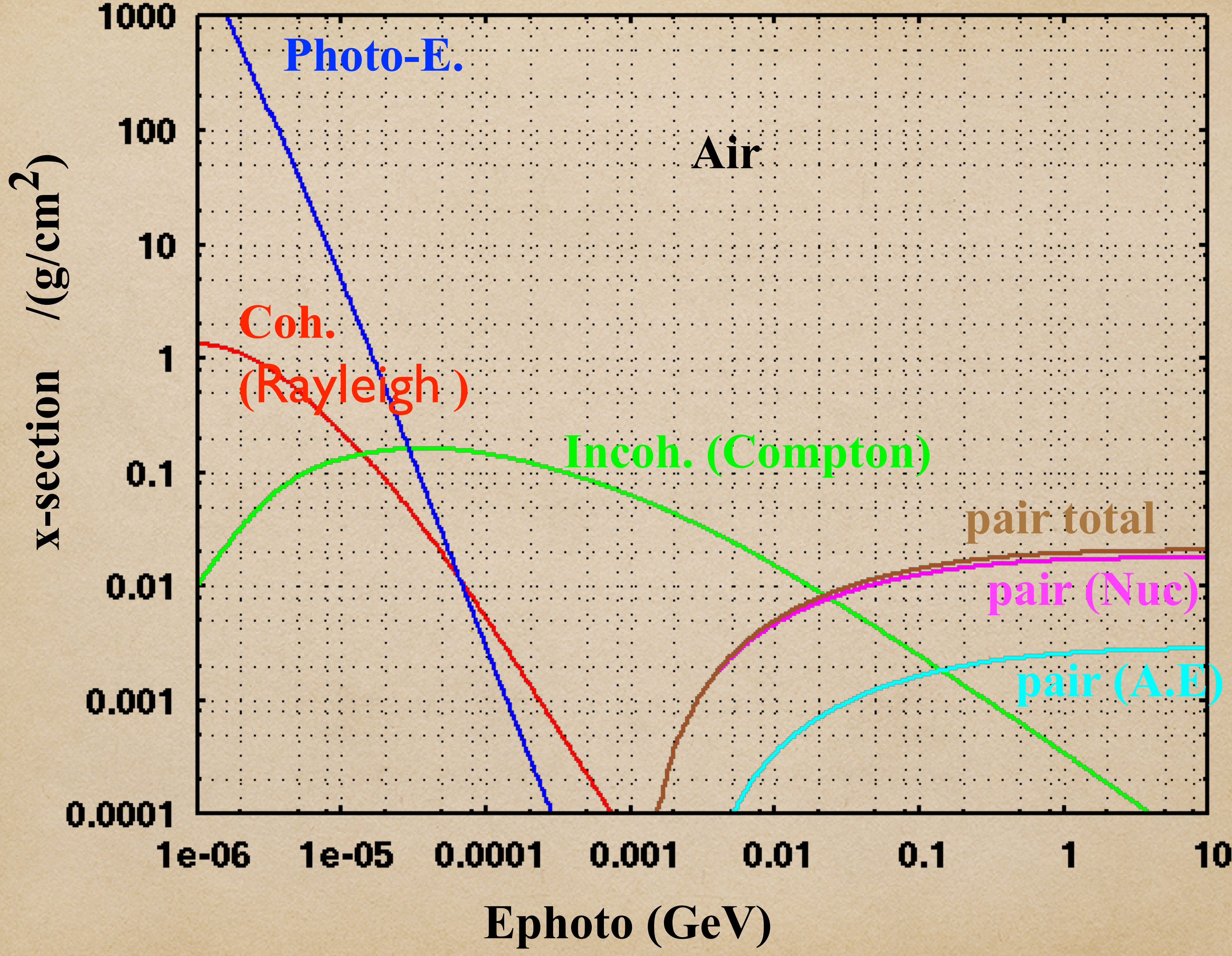


Photo-E.
Air
Coh.
(Rayleigh)
Incoh. (Compton)
pair total
pair (Nuc)
pair (A.E)
1000
100
10
1
0.1
0.01
0.001
0.0001
1e-06
1e-05
0.0001
0.001
0.01
0.1
1
10
x-section /(g/cm2)
Ephoto (GeV)

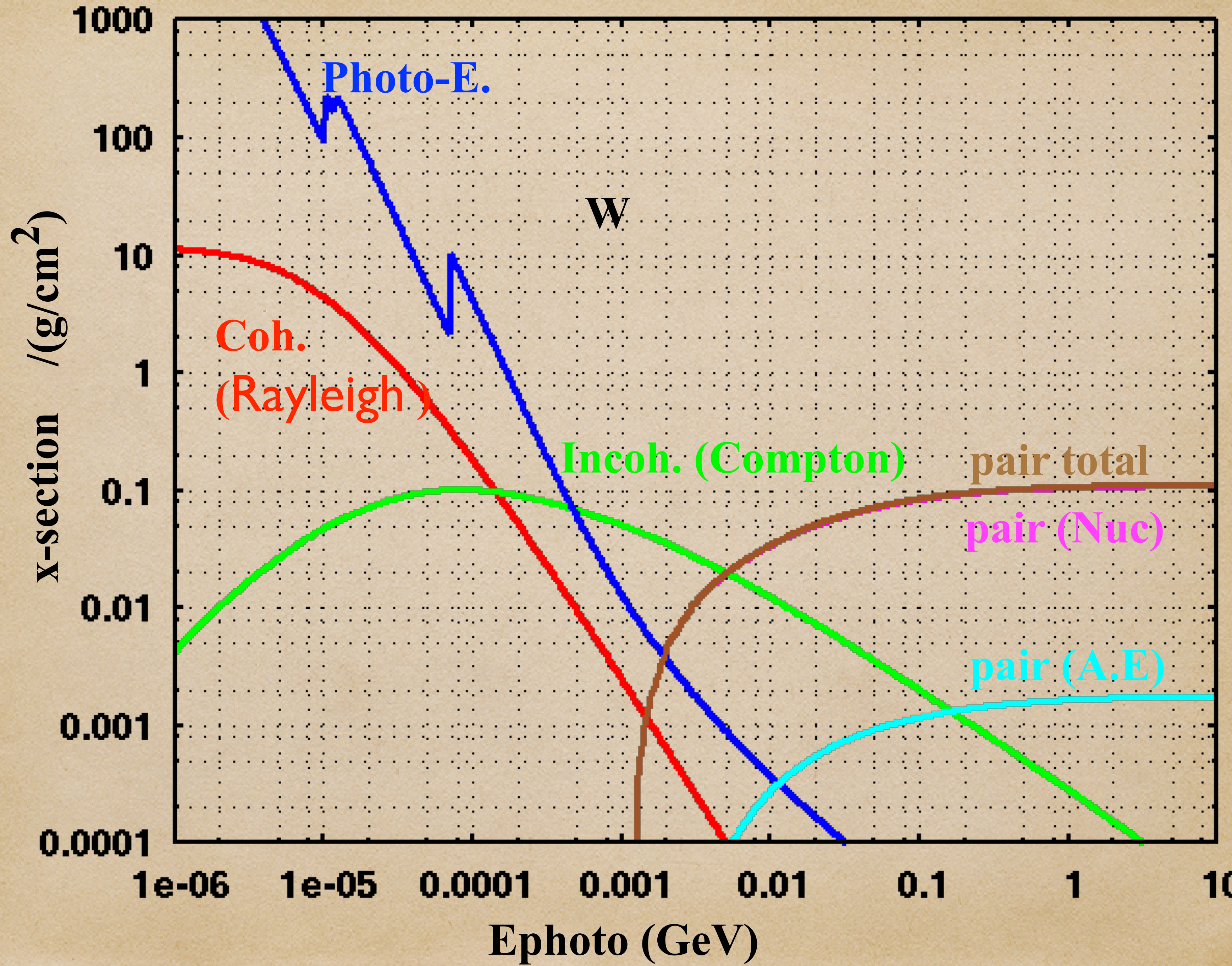


Photo-E.
W
Coh.
(Rayleigh)
Incoh. (Compton)
pair total
pair (Nuc)
pair (A.E)
1000
100
10
1
0.1
0.01
0.001
0.0001
1e-06
1e-05
0.0001
0.001
0.01
0.1
1
10
x-section /(g/cm2)
Ephoto (GeV)

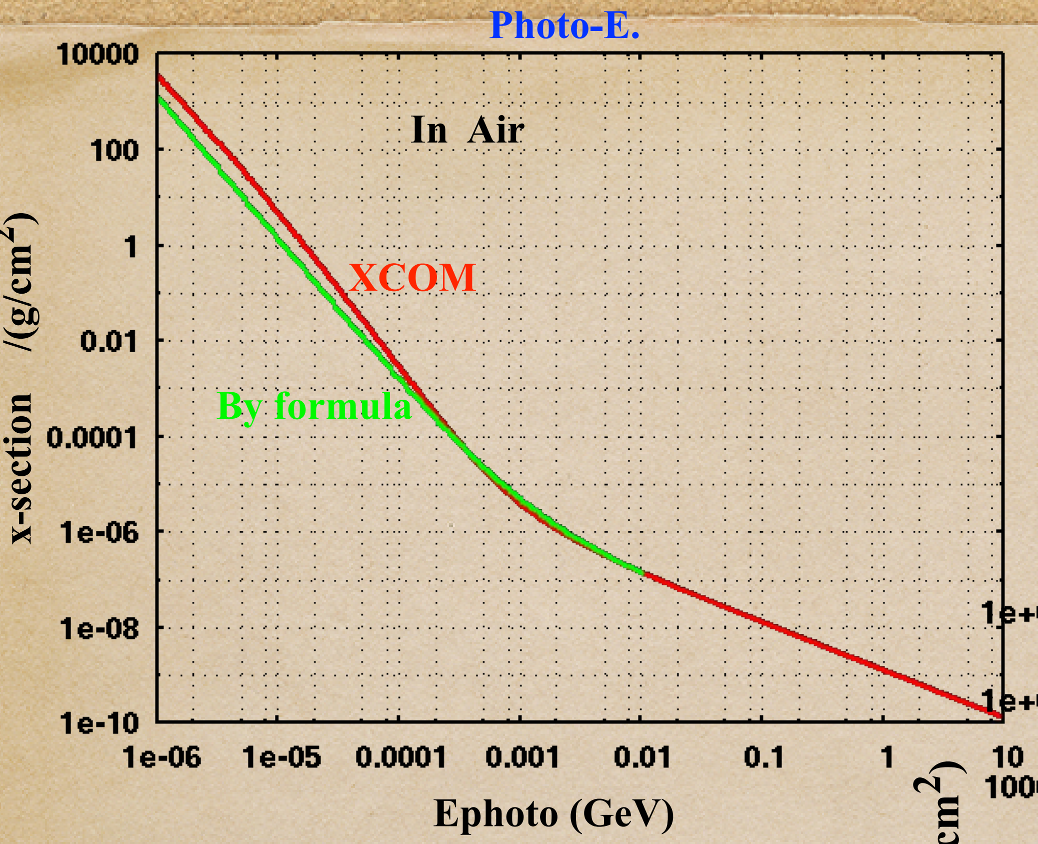


Photo-E.
In Air
XCOM
By formula
x-section /(g/cm^2)
Ephoto (GeV)

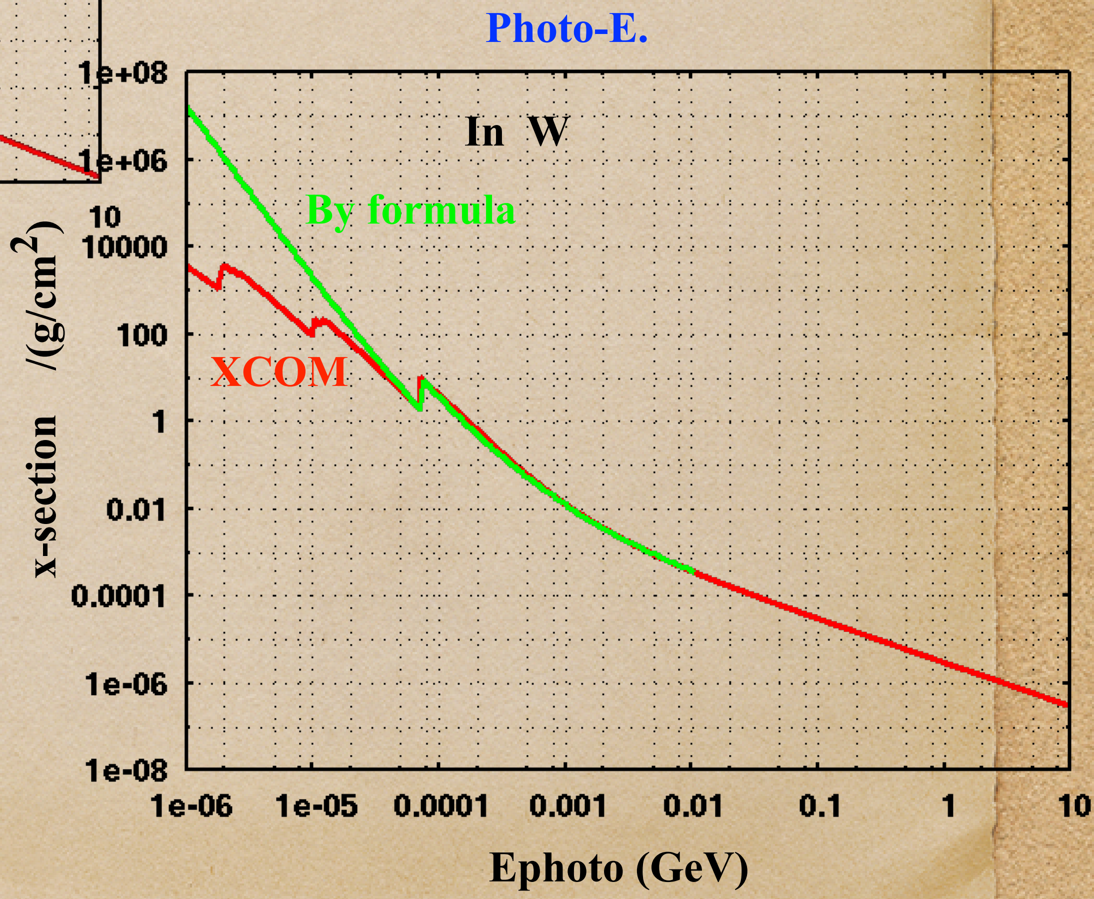
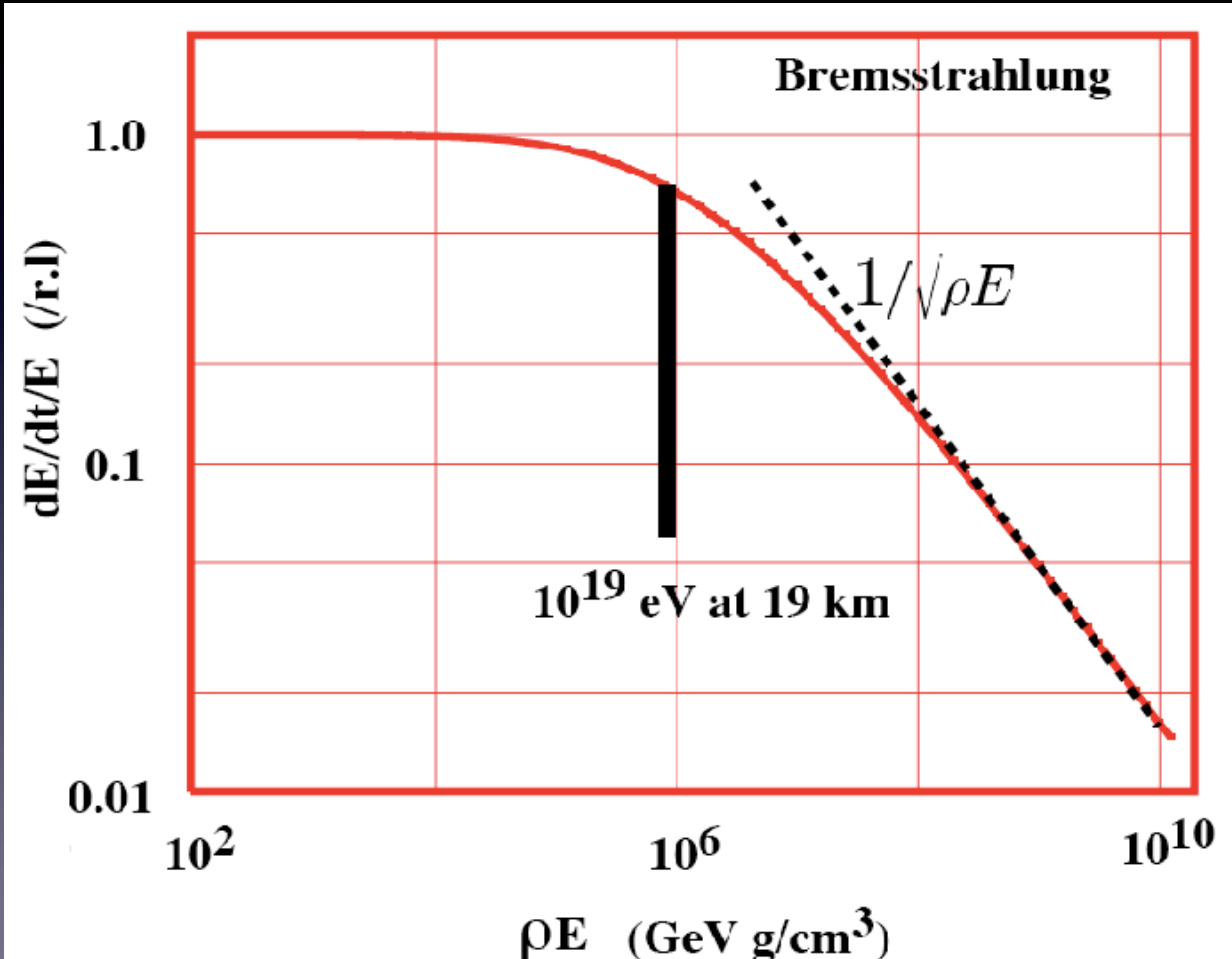


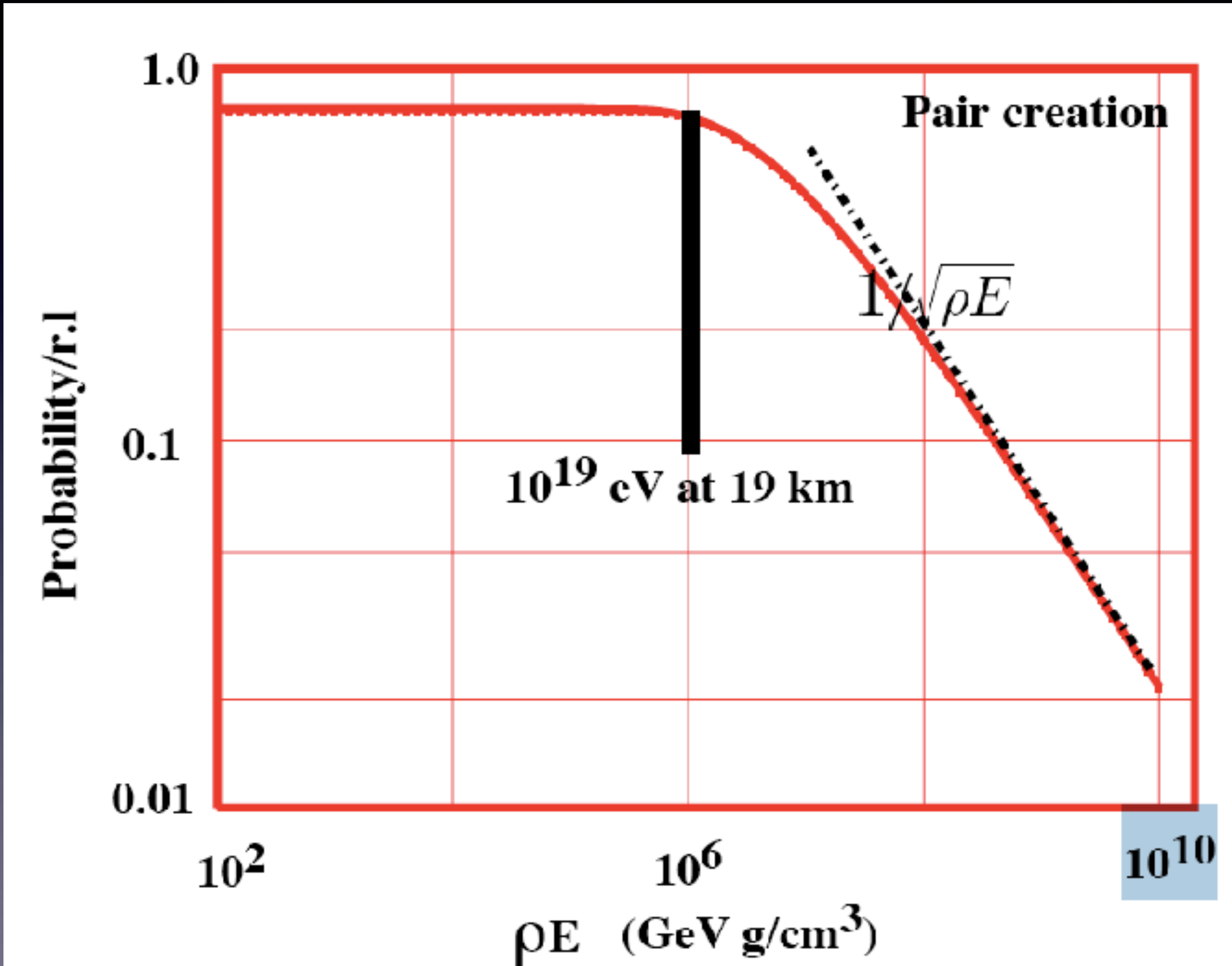
Photo-E.
In W
By formula
XCOM
x-section /(g/cm^2)
Ephoto (GeV)

LPM effect



Bremsstrahlung
1.0
0.1
0.01
dE/dt/E (/r.l)
$1/\sqrt{\rho E}$
10^{19} eV at 19 km
10^2
10^6
10^{10}
ρE (GeV g/cm^3)

LPM effect



1.0
0.1
0.01
Probability/r.l
Pair creation
$1/\sqrt{\rho E}$
10^{19} eV at 19 km
10^2
10^6
10^{10}
ρE (GeV g/cm³)

LPM really exists ?

• SLAC exp.

- P.L. Anthony, et al Phys.Rev.Lett. 1995. 8, 25GeV ~6% diff.
- // Phys. ReV.D 1997. 8, 25GeV. 5~8% diff
  - Klein Rev.Mod. Phys. Vol.71, 1999

• CERN exp.

- Hansen et al. Phys. ReV. D 2004. 150~290 GeV. good
  - More refined theory by Baier & Kadkov, Phys.Rep. vol.409. 2005—>worse at high energies.
- Yoshida et al. ICRC2013, 0733. Emulsion. 50-250GeV
  - Yanagisawa et al. ICRC2013,0732. Geant4 vs Epics

• Cosmic Ray

- K.K Phys. Rev. D Vol.31, 1985
  - 100TeV region

Hansen et al Exp. bias large

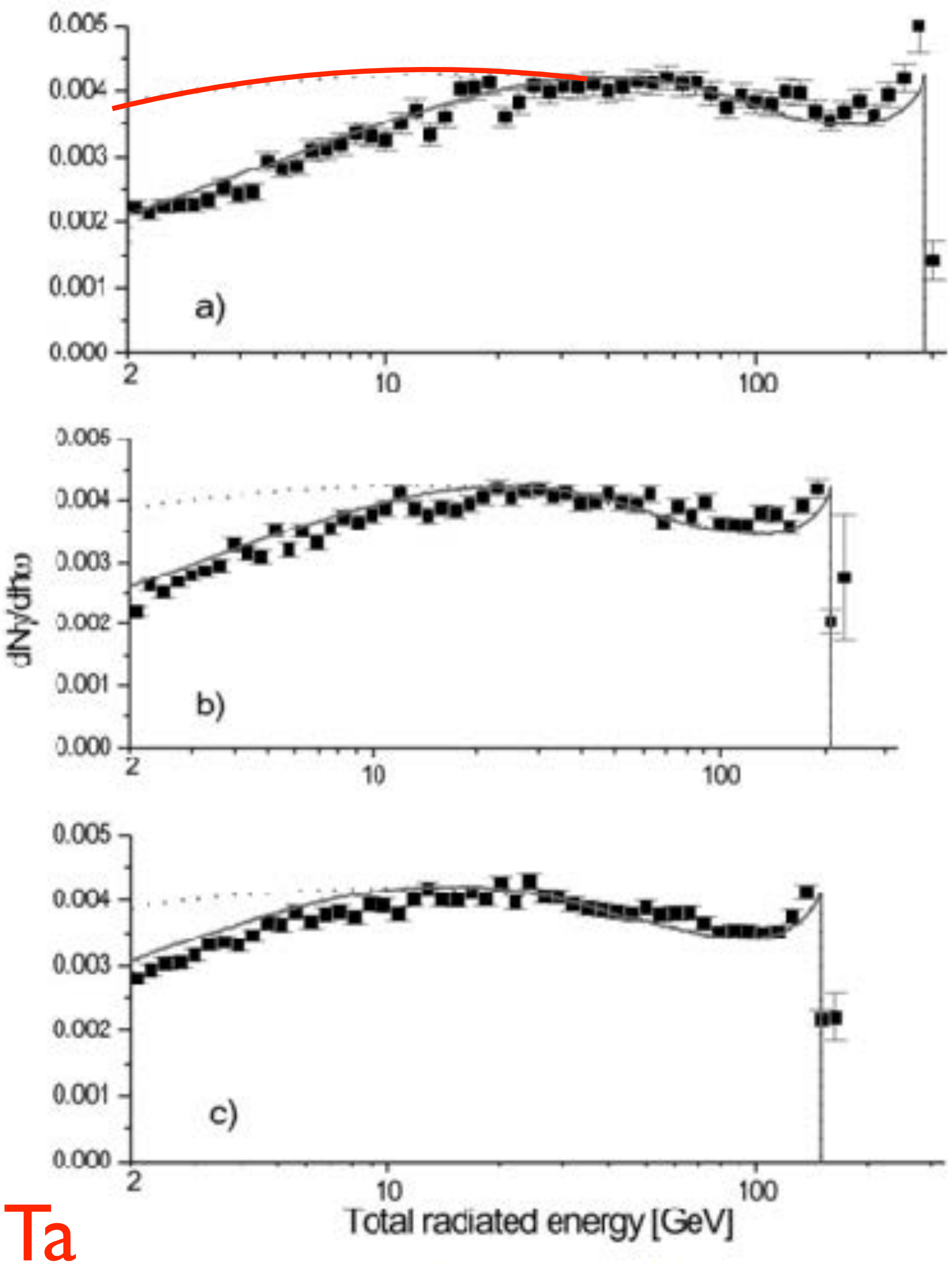


FIG. 10. As Fig. 9, but for tantalum.

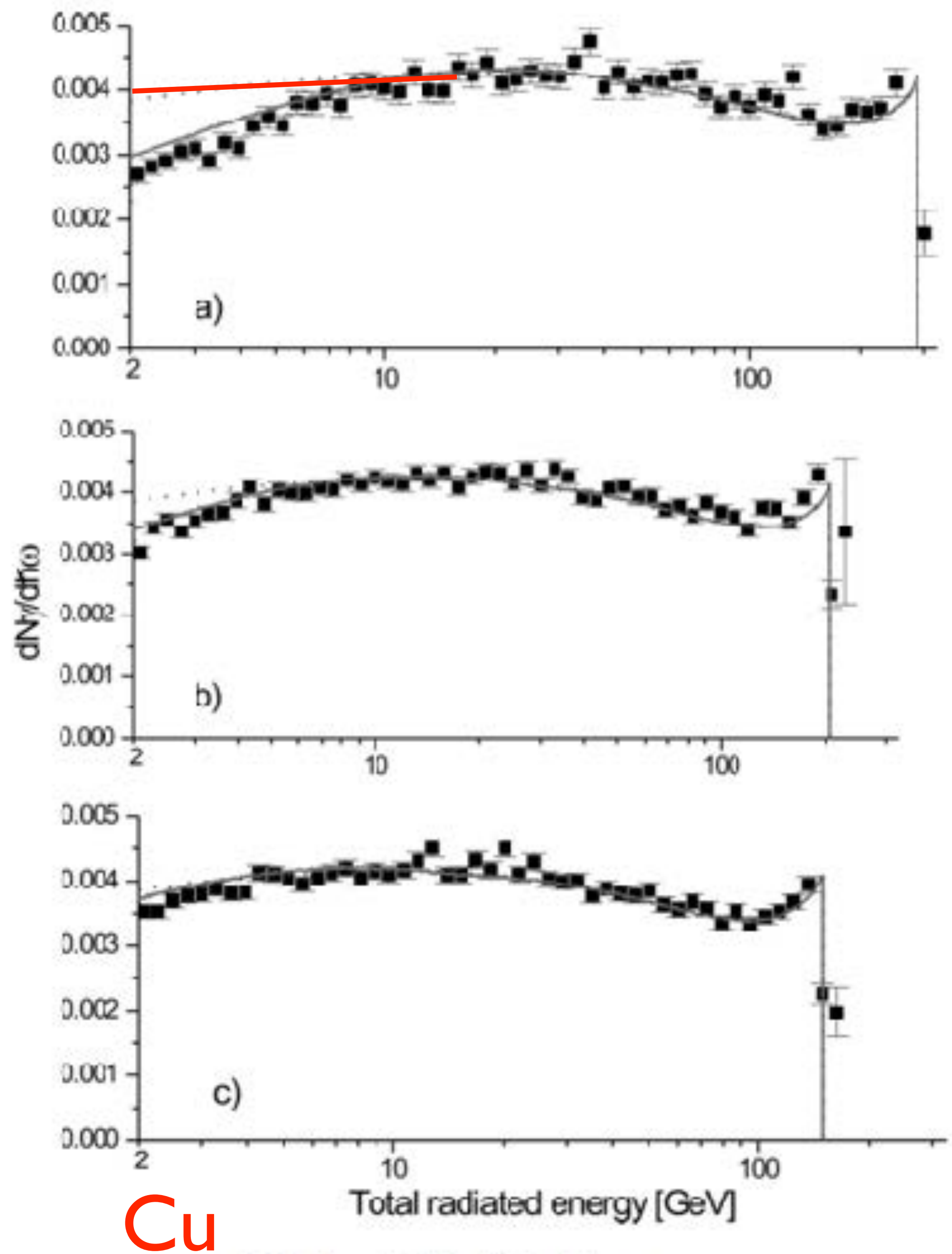


FIG. 11. As Fig. 9, but for copper.

Hansen et al

Exp. bias large

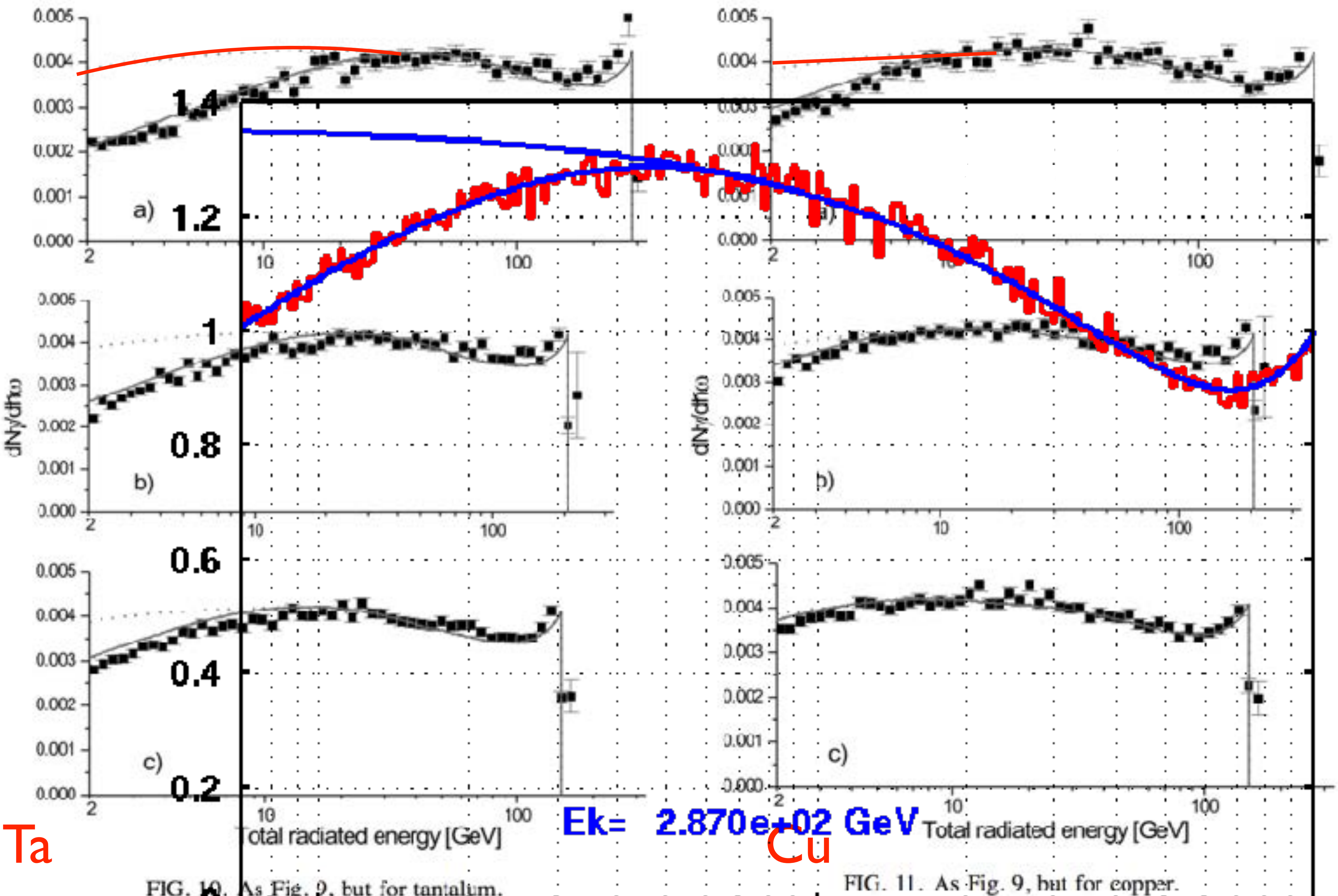
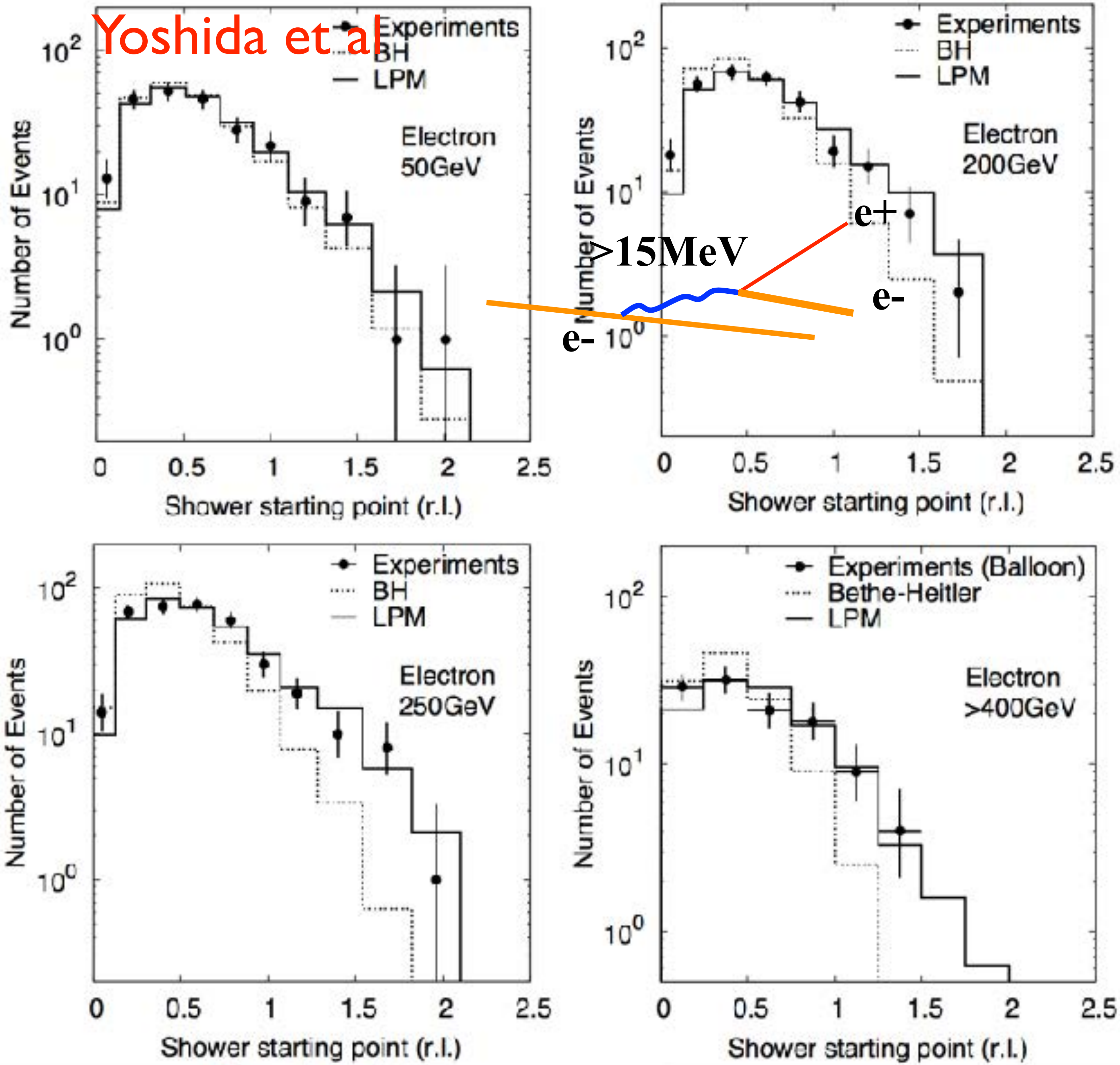


FIG. 10. As Fig. 9, but for tantalum.

FIG. 11. As Fig. 9, but for copper.


Yoshida et al
Experiments
BH
LPM
Electron
50GeV
Number of Events
Shower starting point (r.l.)
Electron
200GeV
e+
>15MeV
e-
e-
Electron
250GeV
Experiments (Balloon)
Bethe-Heitler
Electron
>400GeV

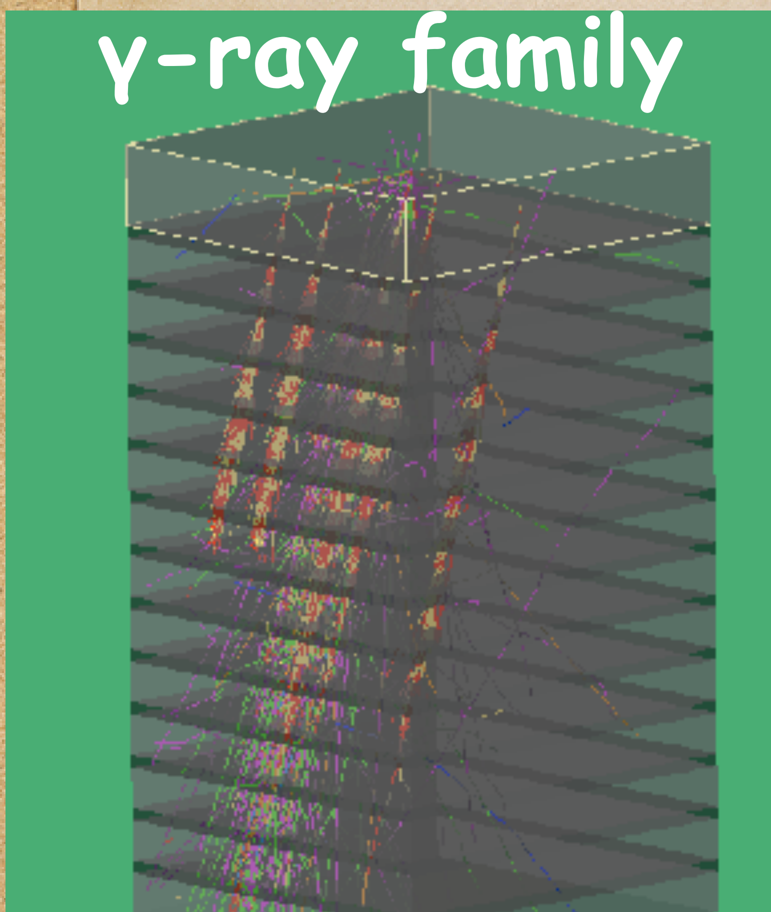
PHYSICAL REVIEW D VOLUME 31, NUMBER 11 1 JUNE 1985

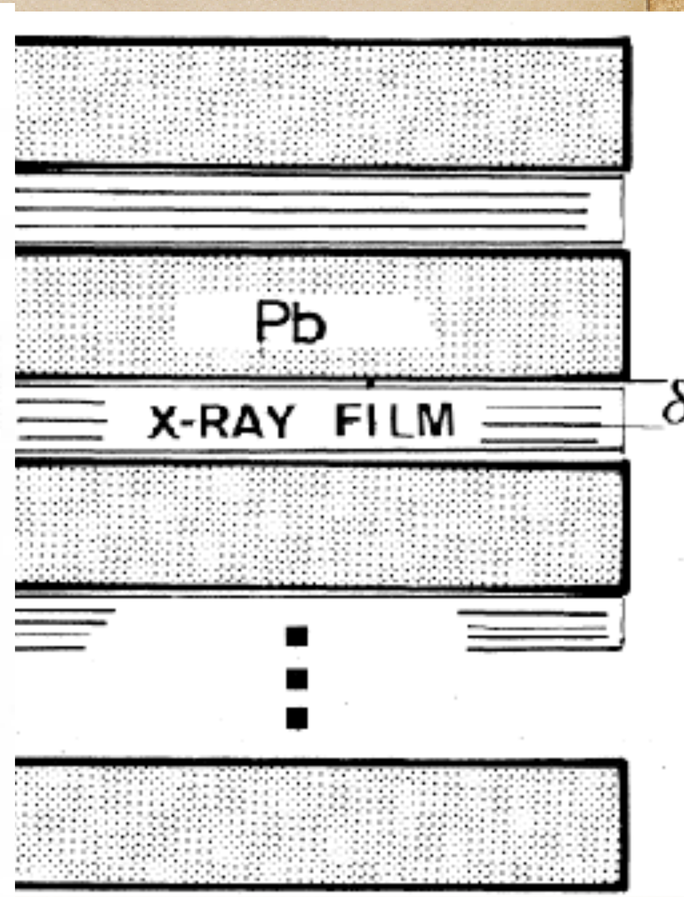
Experimental examination of the Landau-Pomeranchuk-Migdal effect by high-energy electromagnetic cascade showers in lead

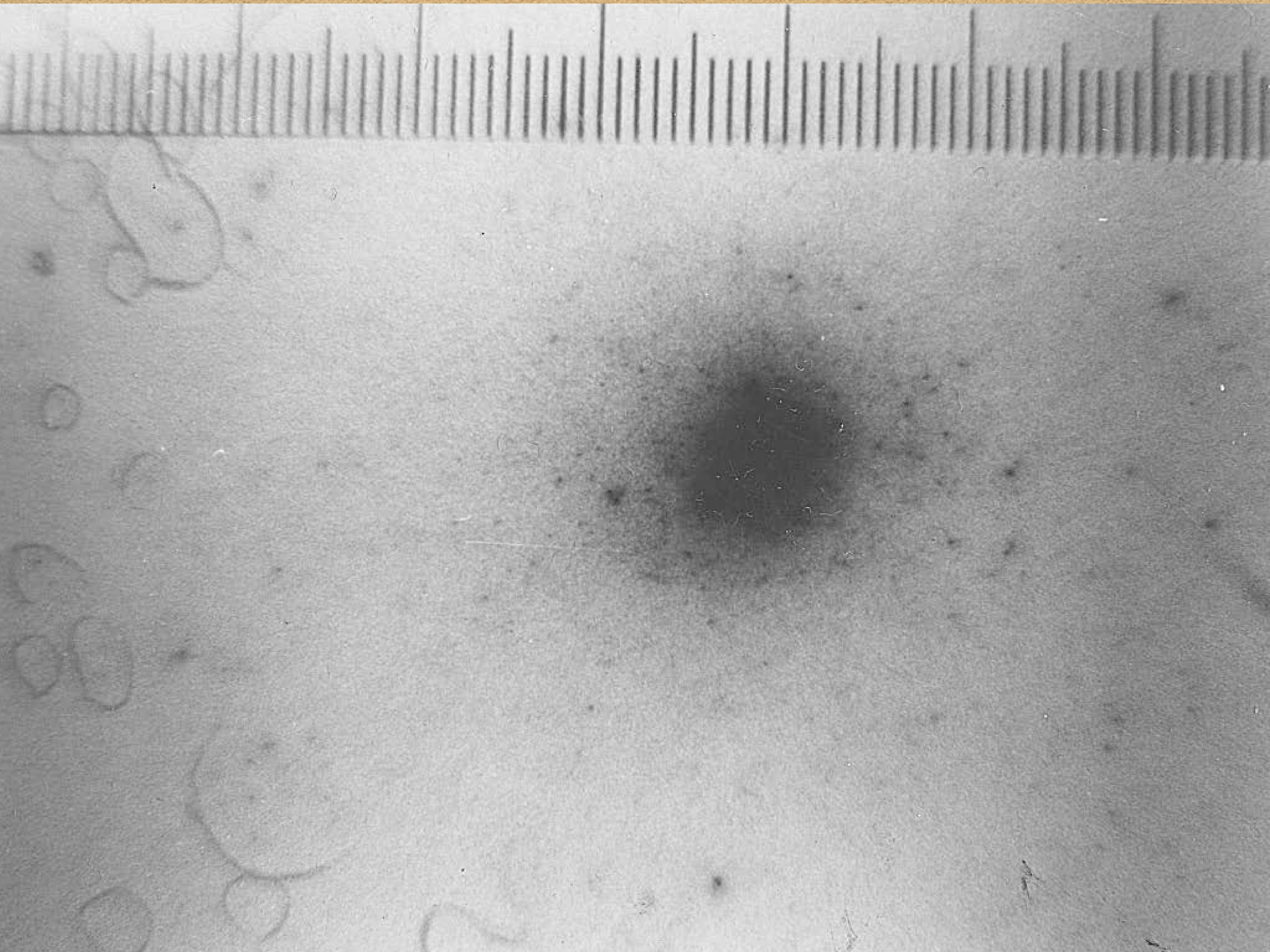
K. Kasahara
Institute for Cosmic Ray Research, University of Tokyo, Tanashi, Tokyo
(Received 27 September 1984)

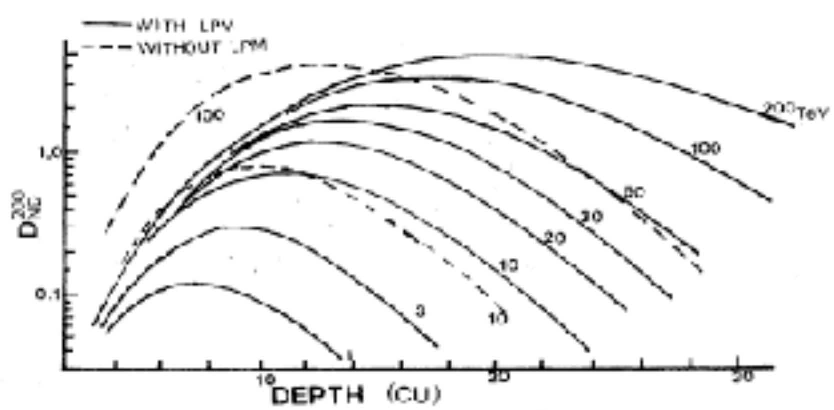
100TeV region

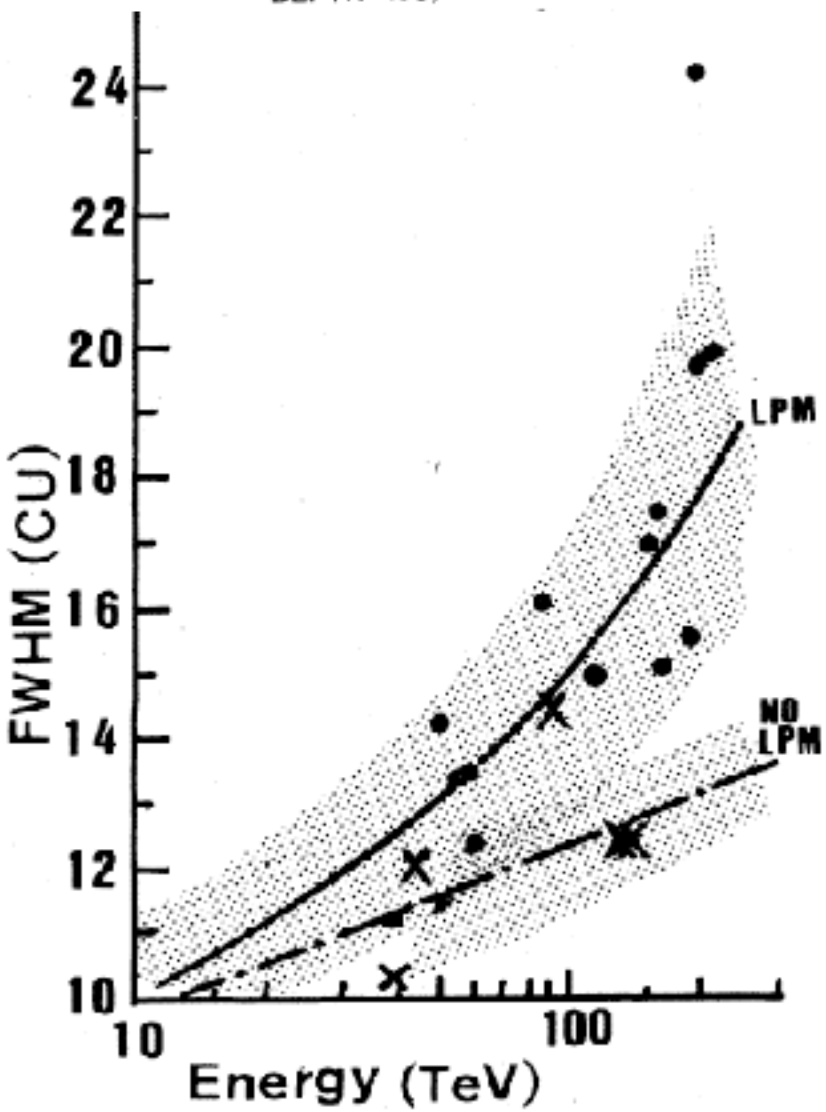
Emulsion Chamber

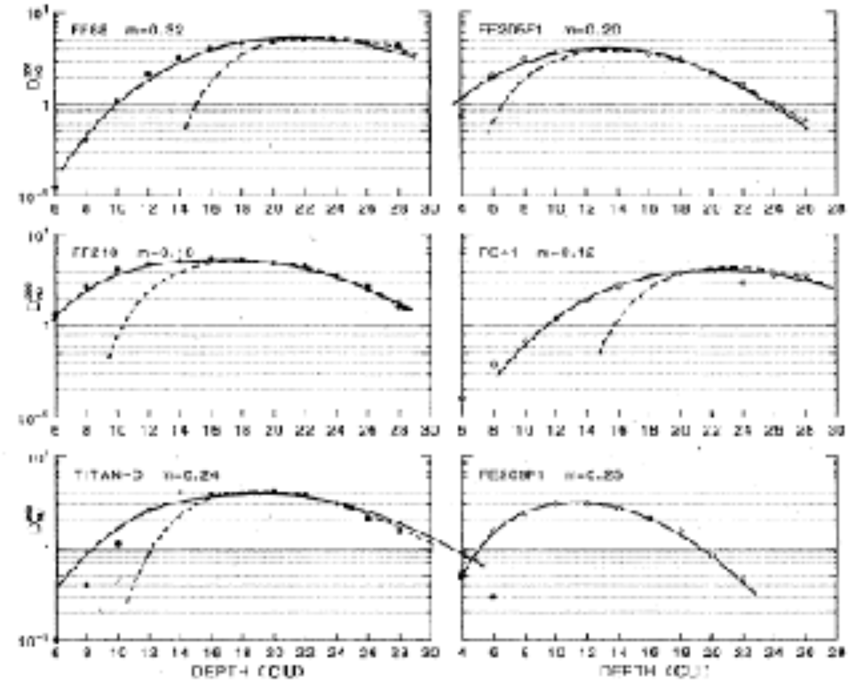


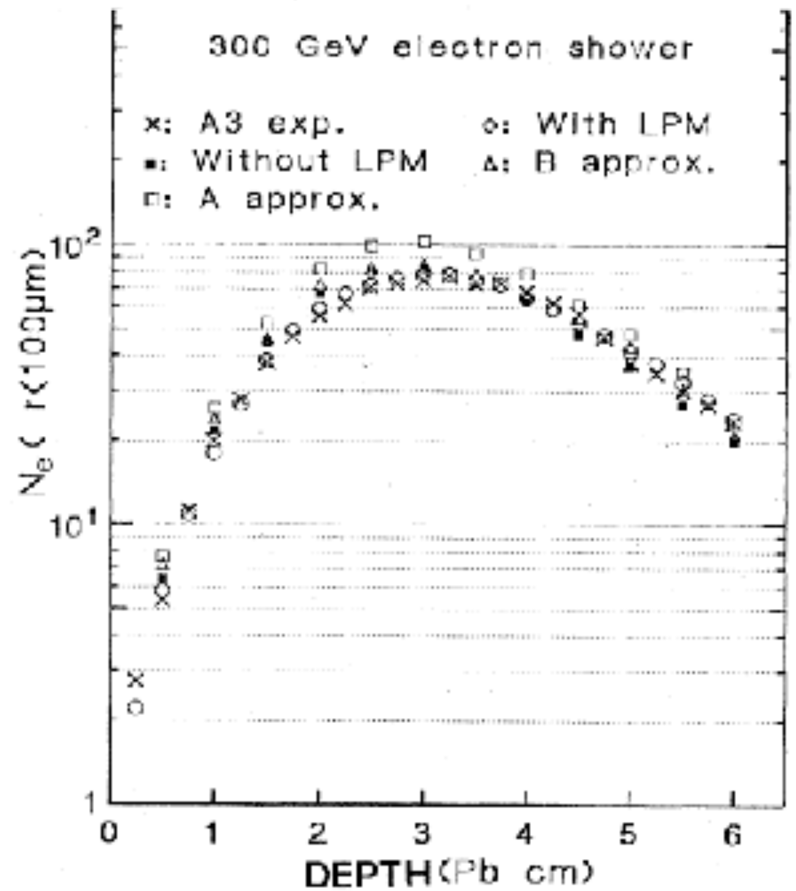





WITH LPM
WITHOUT LPM
200 TeV
100
50
20
10
3
1
DEPTH (CU)


FWHM (CU)
LPM
NO LPM
Energy (TeV)


DEPTH (CU)


300 GeV electron shower
×: A3 exp.
○: With LPM
■: Without LPM
Δ: B approx.
□: A approx.
N_e (r<100μm)
DEPTH (Pb cm)

“LPM” effect surely exists

- Absolute scale; to be studied more
- For hadronic showers, effect could be neglected at < 10^20 eV

Mag. Effect at ultra high energies

$$\Upsilon = \frac{E_e}{m}\frac{B}{B_c} \qquad \chi = \frac{1}{2}\frac{E_\gamma}{m}\frac{B}{B_c}$$

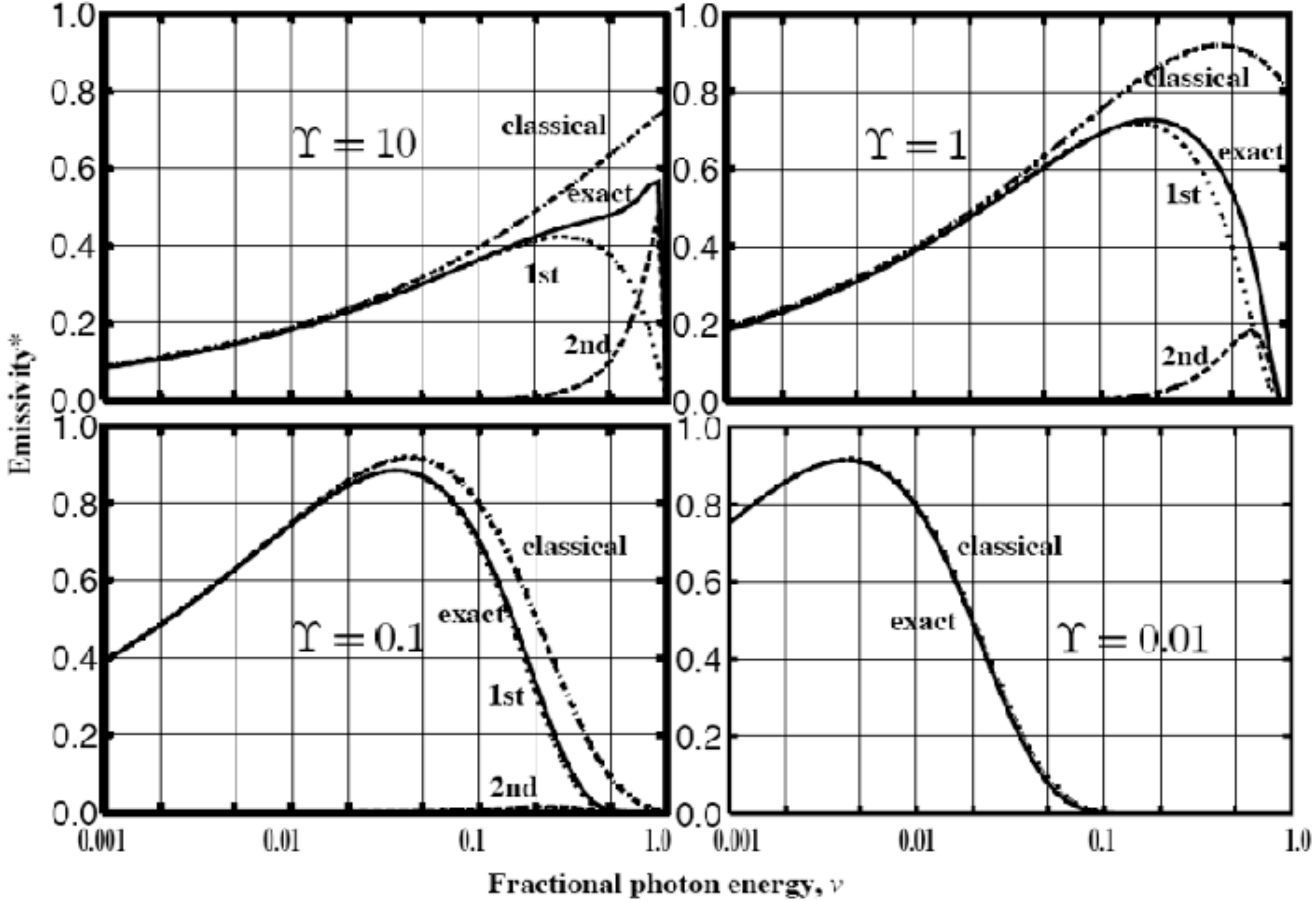
$$B_c = 4.3 \times 10^{13}\text{gauss}, \qquad B \sim 0.3\text{gauss}$$

$$\Upsilon \sim 1 \Rightarrow E_e \sim 5 \times 10^{19}\ \text{eV}$$

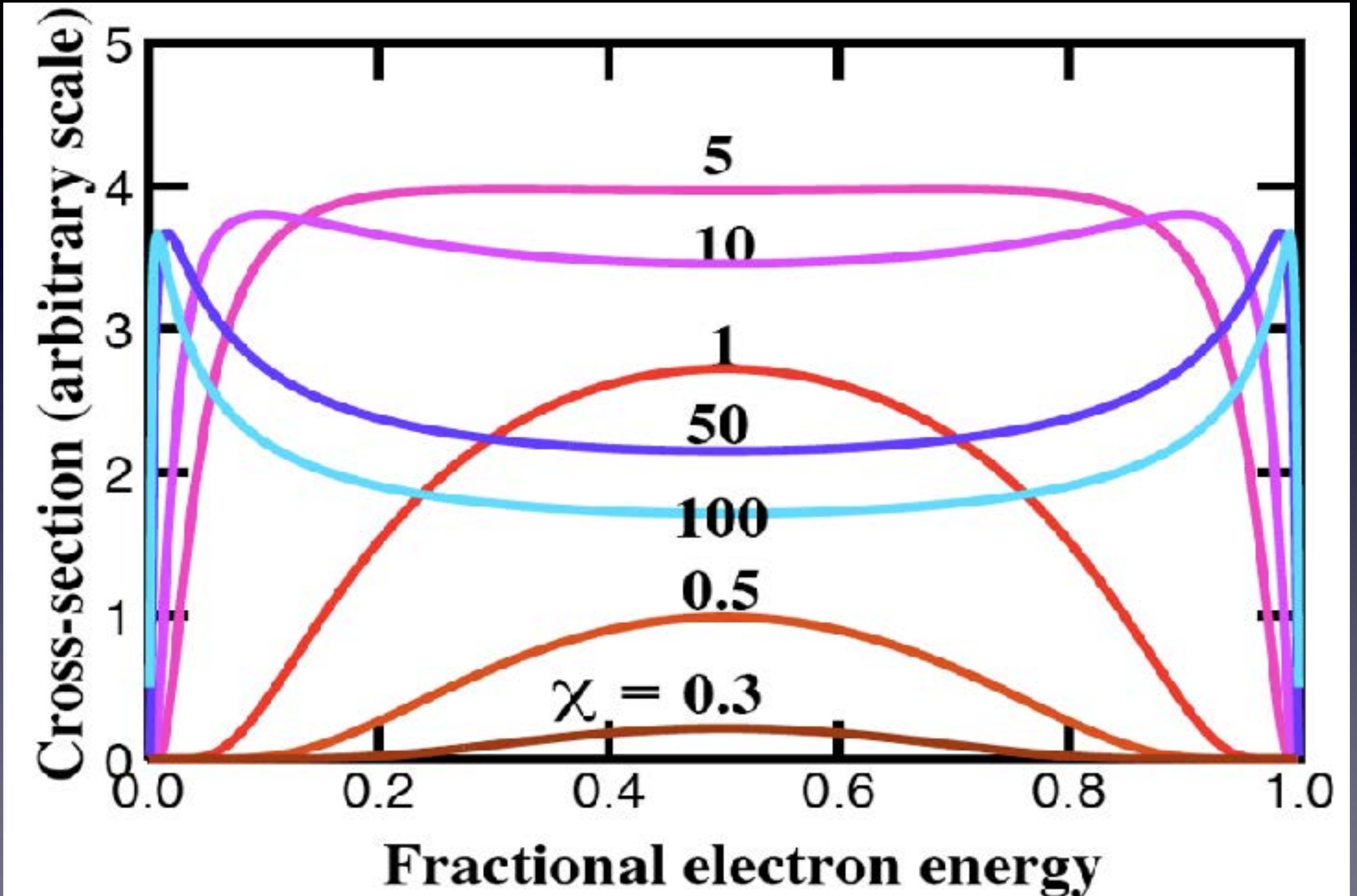
$$\chi \sim 1 \Rightarrow E_\gamma \sim 10^{20}\ \text{eV}$$

M.G.Baring: Mon. Not. R. astr. Soc. 235(1988) 51-78

Mag. Brems

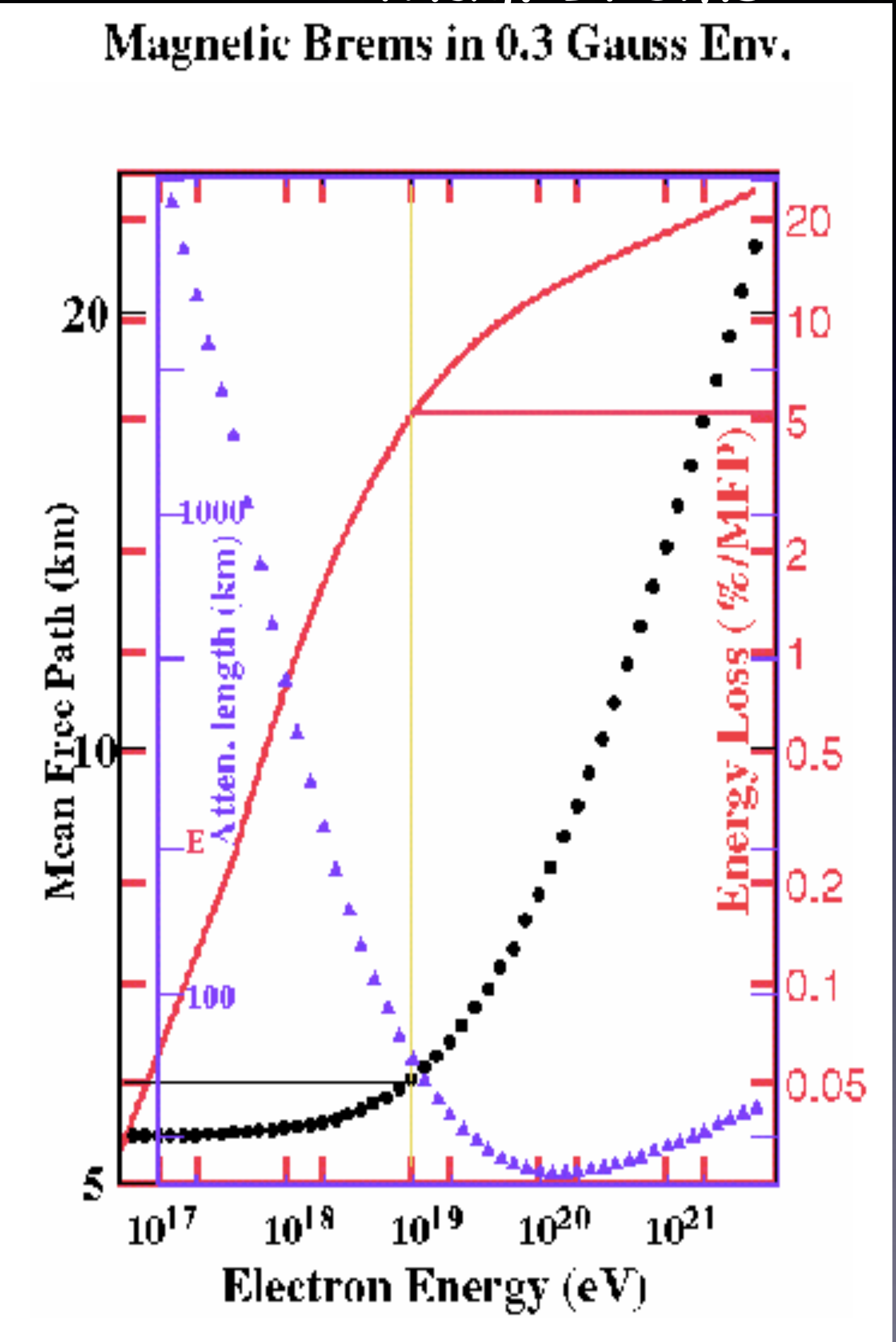


Mag. pair cre.

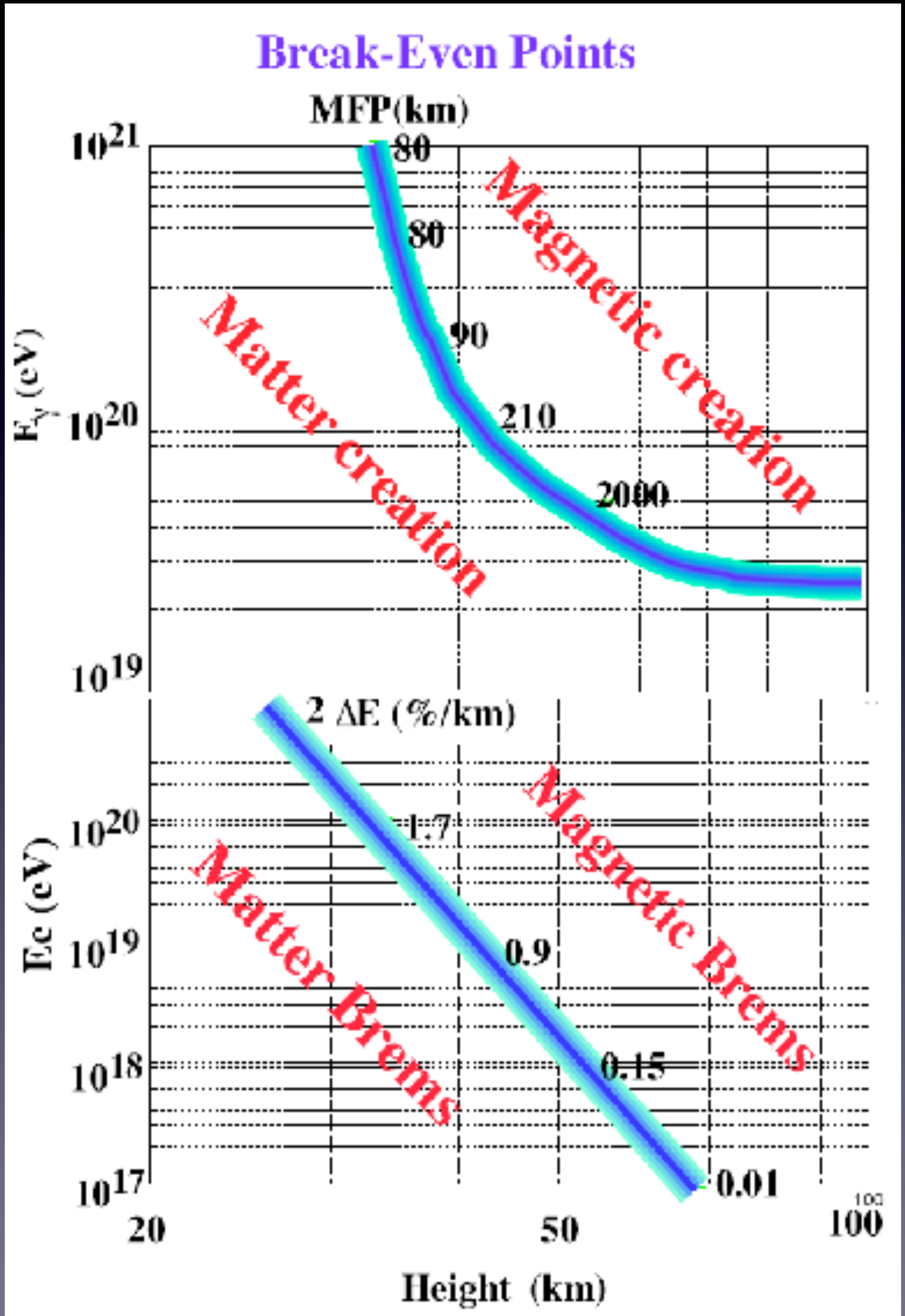


Cross-section (arbitrary scale)
5
4
3
2
1
0
0.0
0.2
0.4
0.6
0.8
1.0
Fractional electron energy
5
10
1
50
100
0.5
χ = 0.3

Mag. Brems

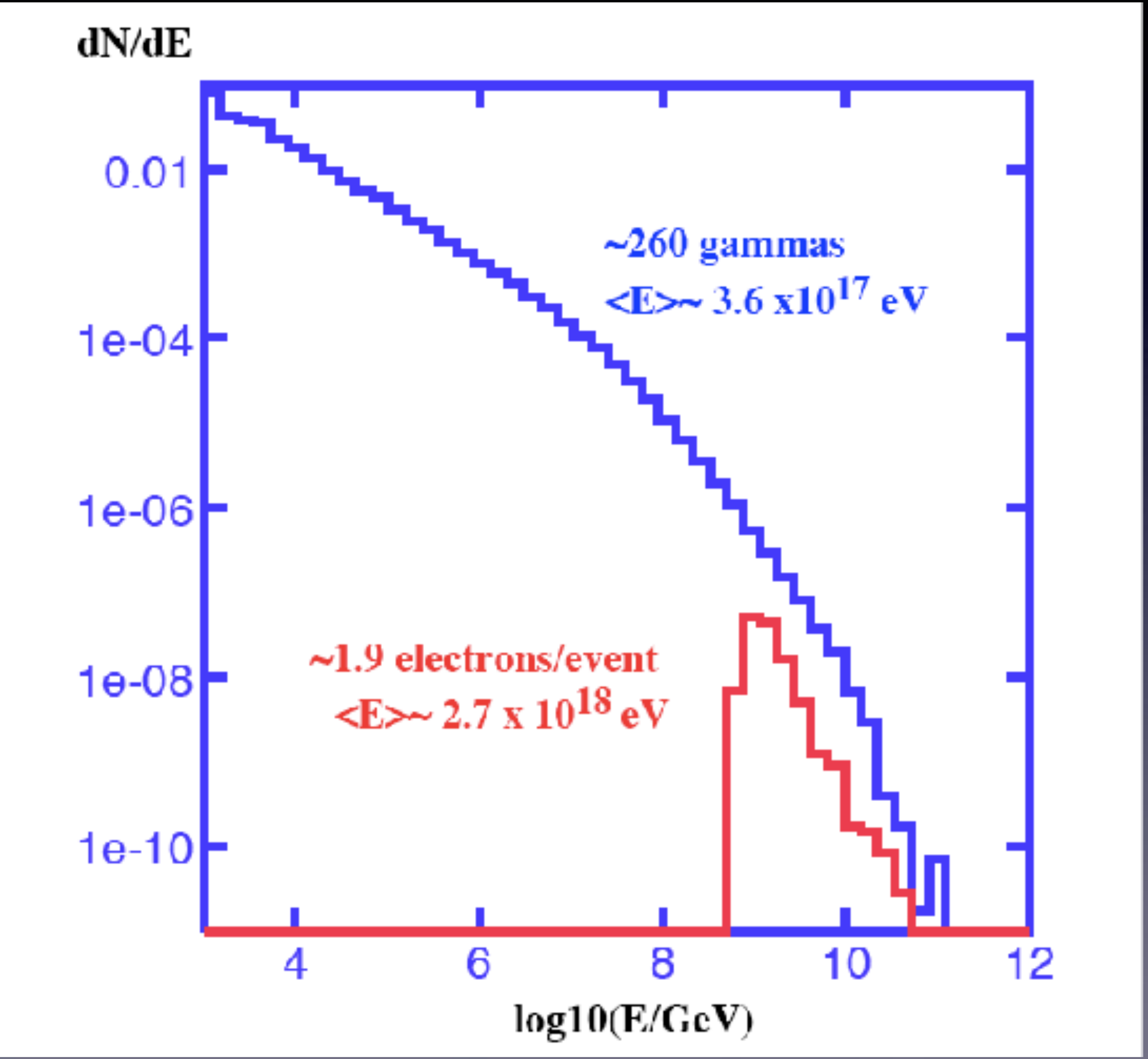


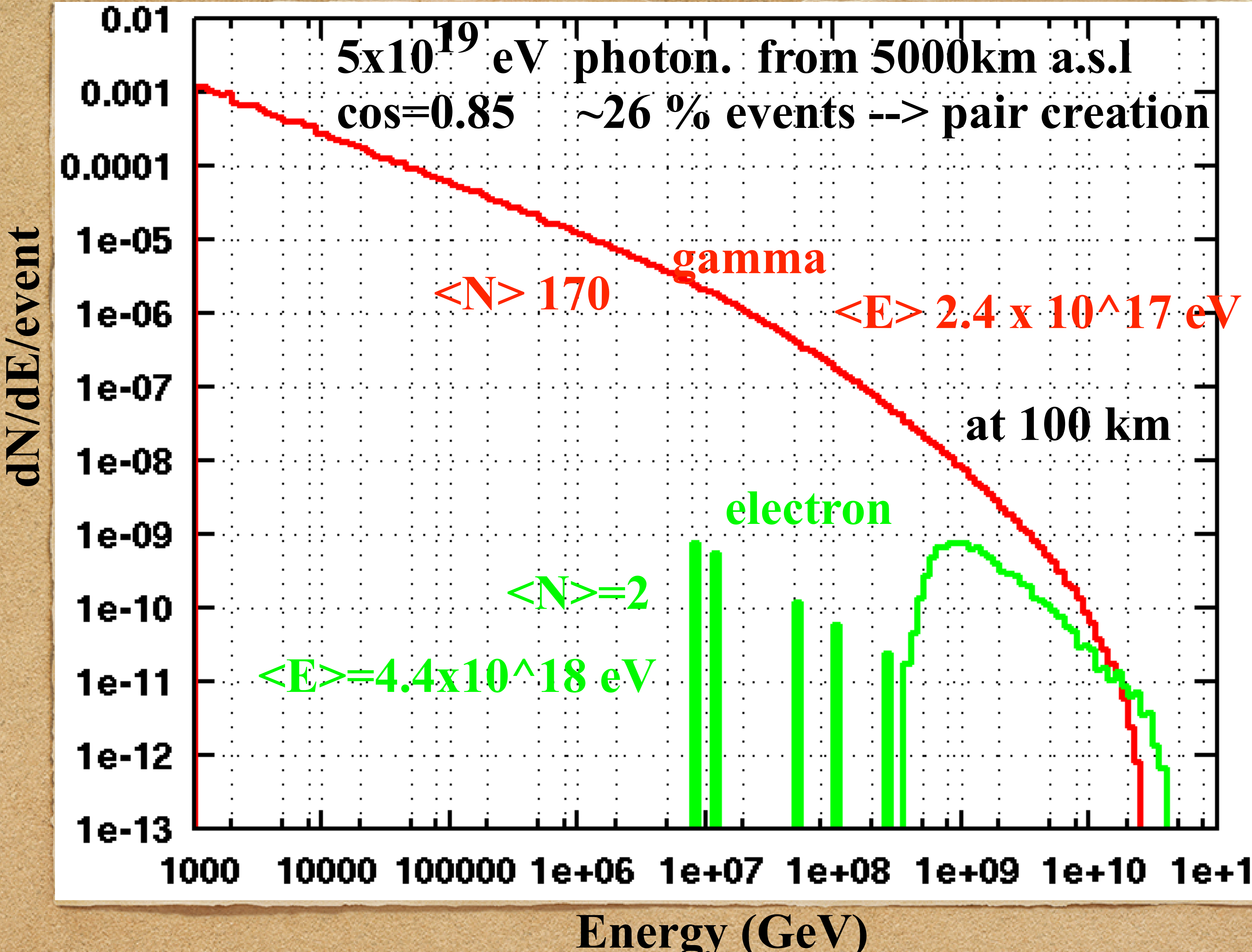
Magnetic Brems in 0.3 Gauss Env.
Mean Free Path (km)
Atten. length (km)
Energy Loss (%/MFP)
Electron Energy (eV)
20
10
5
1000
100
E
20
10
5
2
1
0.5
0.2
0.1
0.05
10^{17}
10^{18}
10^{19}
10^{20}
10^{21}



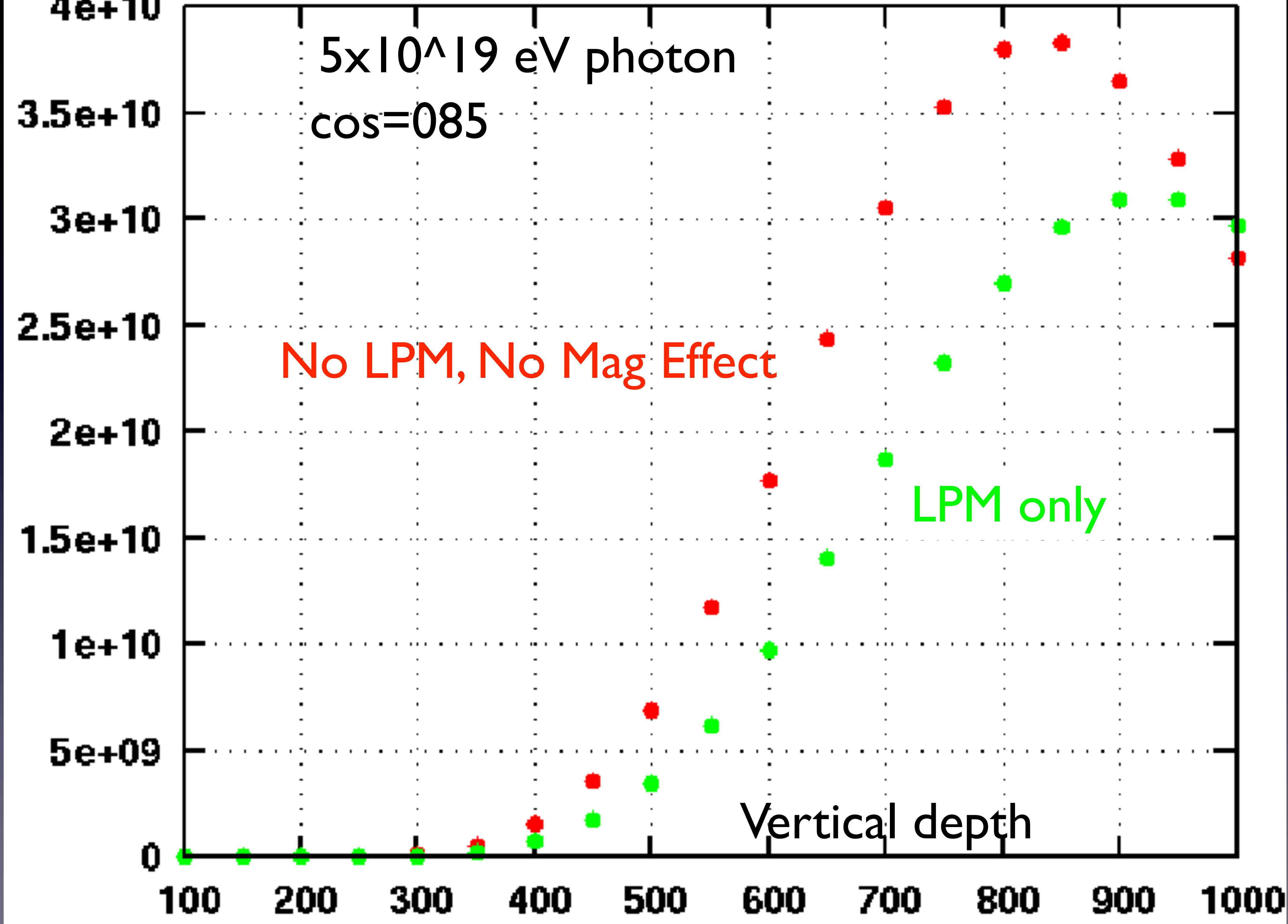
Break-Even Points
MFP(km)
E_γ (eV)
10^{21}
10^{20}
10^{19}
80
80
90
210
2000
Magnetic creation
Matter creation
2 ΔE (%/km)
Ec (eV)
10^{20}
10^{19}
10^{18}
10^{17}
1.7
0.9
0.15
0.01
Magnetic Brems
Matter Brems
20
50
100
Height (km)

Average energy spectrum of magnetic cascade at 100 km a.s.l for 10^{20}eV photon primary



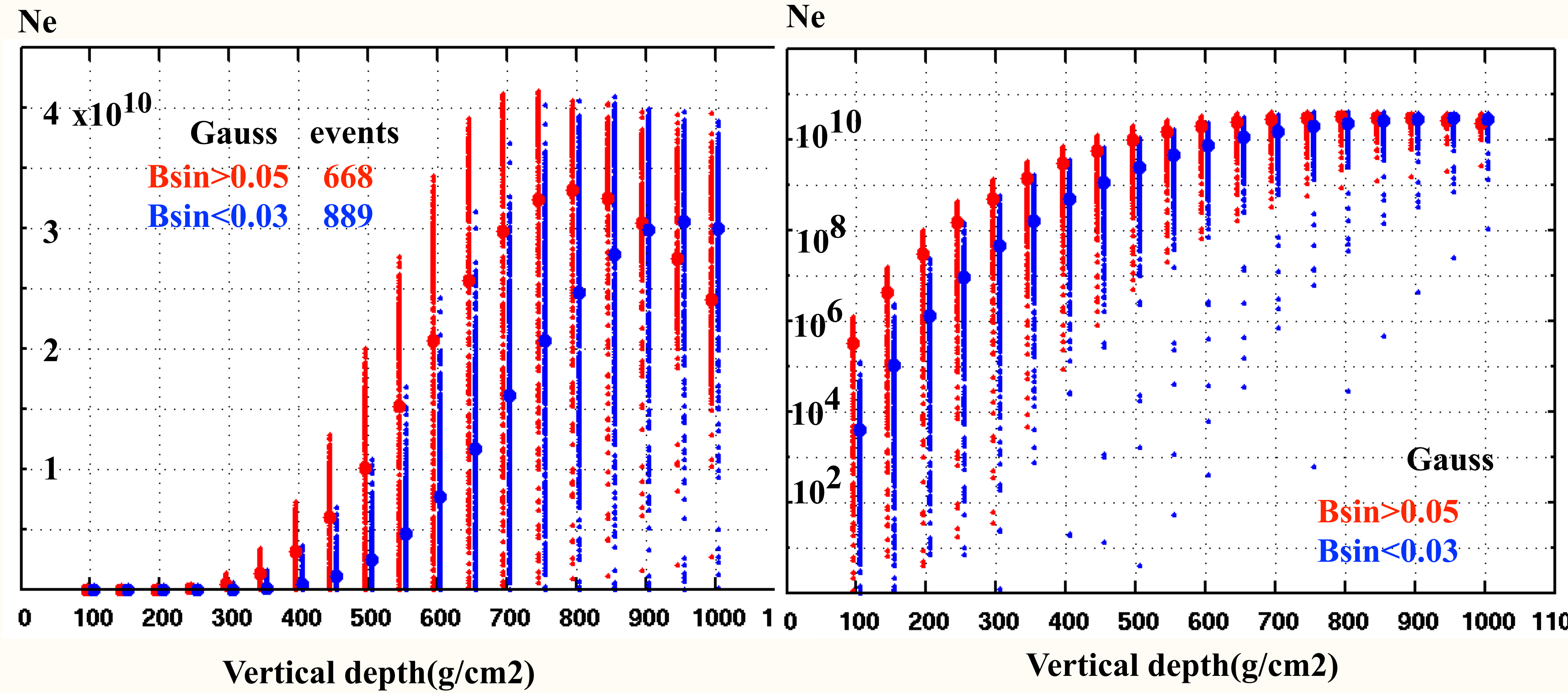


5x10^19 eV photon. from 5000km a.s.l
cos=0.85 ~26 % events --> pair creation
gamma
<N> 170
<E> 2.4 x 10^17 eV
at 100 km
electron
<N>=2
<E>=4.4x10^18 eV
dN/dE/event
Energy (GeV)
0.01
0.001
0.0001
1e-05
1e-06
1e-07
1e-08
1e-09
1e-10
1e-11
1e-12
1e-13
1000
10000
100000
1e+06
1e+07
1e+08
1e+09
1e+10
1e+1

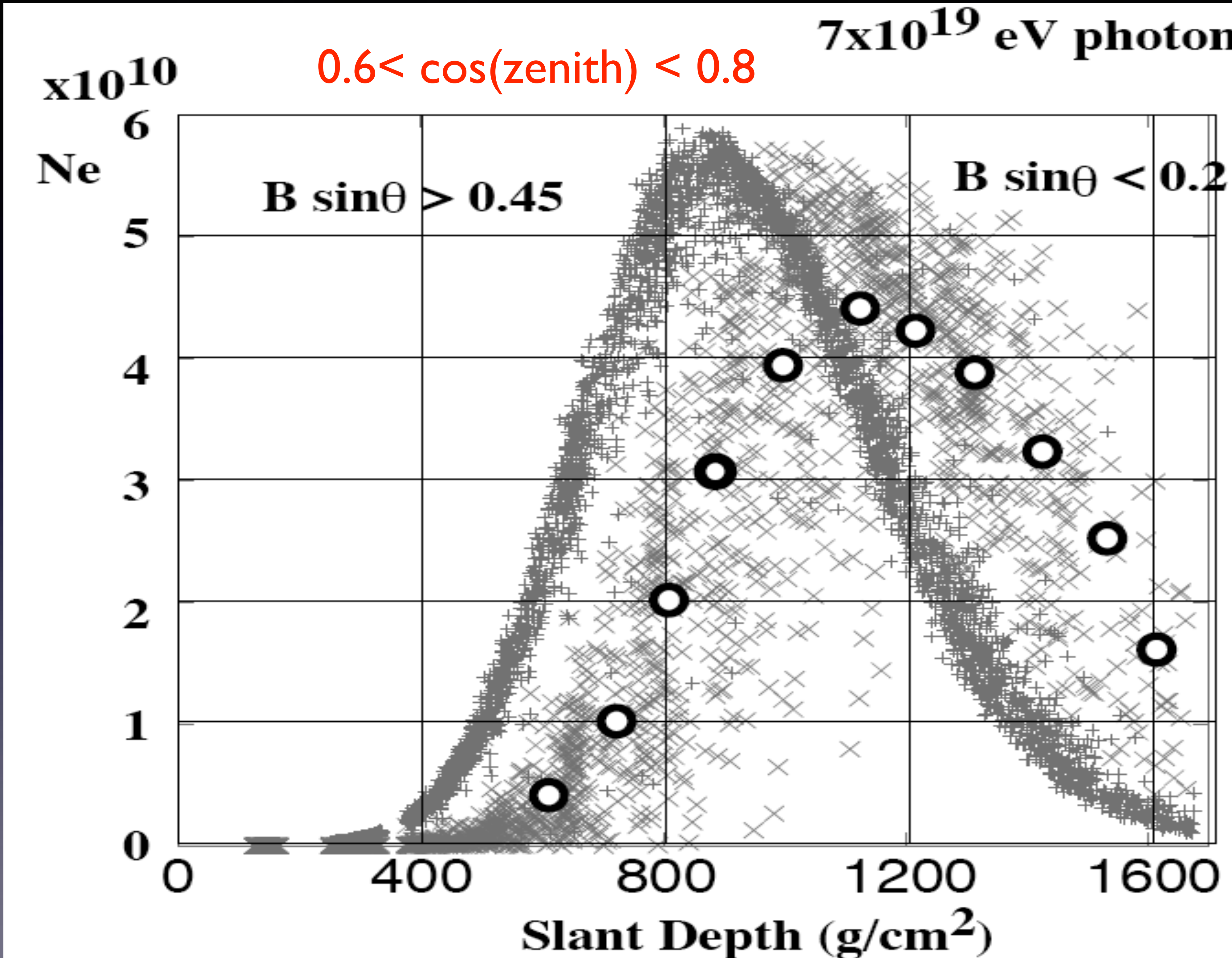


5x10^19 eV photon
cos=085
No LPM, No Mag Effect
LPM only
Vertical depth
4e+10
3.5e+10
3e+10
2.5e+10
2e+10
1.5e+10
1e+10
5e+09
0
100
200
300
400
500
600
700
800
900
1000

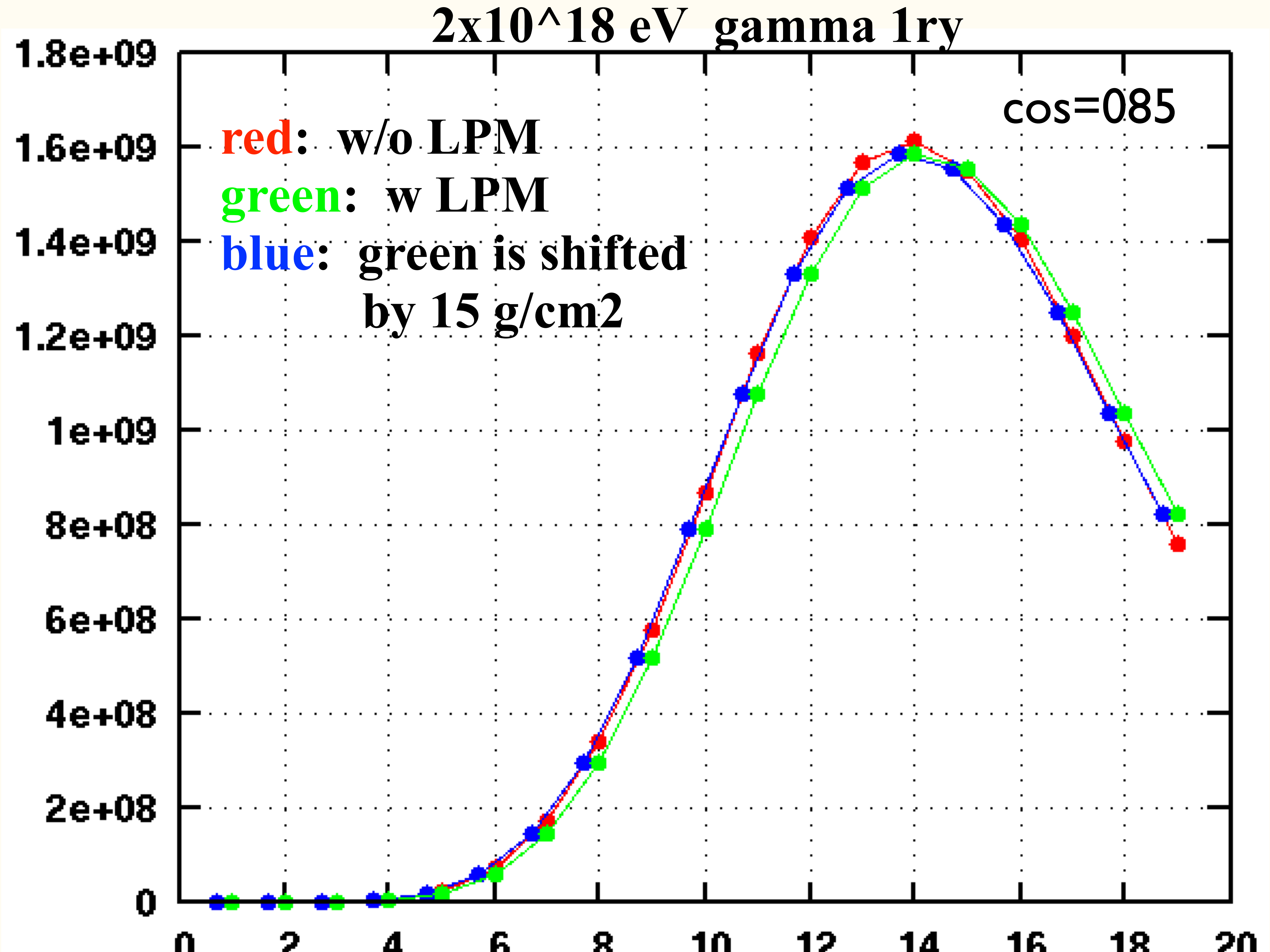
photon 1ry 5×10^{19} eV



LPM + Geomag



7x10^19 eV photon
0.6< cos(zenith) < 0.8
x10^10
Ne
B sinθ > 0.45
B sinθ < 0.2
6
5
4
3
2
1
0
0
400
800
1200
1600
Slant Depth (g/cm^2)



2x10^18 eV gamma 1ry
cos=085
red: w/o LPM
green: w LPM
blue: green is shifted
by 15 g/cm2
1.8e+09
1.6e+09
1.4e+09
1.2e+09
1e+09
8e+08
6e+08
4e+08
2e+08
0
0
2
4
6
8
10
12
14
16
18
20

"LPM" effect surely exists

- Absolute scale; to be studied more
- For hadronic showers, effect could be neglected at < 10^20 eV
- For photon showers, must be careful even at 2x10^18 eV.
- >3x10^19eV, Magnetic and LPM effects works strongly. Need careful analysis of the arrival direction and B