Uncertainties beyond 10-100TeV

of

Gamma ray & CR phenomena :

「**QG effects**
on the detection method etc.」

by T. Kifune

１０－１００　TeV　以上の
ガンマ線には
通常･従来の検出方法を
適用できない

The usual / conventional method of detecting gamma rays can not be applied to gamma rays beyond 10 -100 Tev .

Some comments ....

- **Relative Delay time = -5.5 ± 10.9 ± 10.3 [sec TeV^{-1}]**

HESS Beijing 2011, Bolmont et al.

PKS 2155-304, z=0.116, d = 1.4 × 10^9 [ly] = 4.2 × 10^{16} [light sec]

$M > 2.1 \times 10^{27}$ eV = 0.6 M_{planck}

$$M \approx M_{PL} = \sqrt{\frac{hc}{2\pi G}} = 1.2 \times 10^{28} [eV / c^2]$$

- **Modified p-E relation**

$$P^2 c^2 = E^2 - m^2 c^4 + \xi \frac{E^3}{M c^2}$$

$$v = \frac{dE}{dP} = c(1 - \frac{E}{Mc^2}) = c(1 - \frac{E}{1TeV} \cdot 10^{-16})$$

- **Systematic errors**

emission time within (1-10) second

Emission size within 10^{10-11} cm

Some comments ……….

- **Relative Delay time = -5.5 ±10.9 ±10.3 [sec TeV^{-1}]**

HESS Beijing 2011, Bolmont et al.

OPERA **Oscillation Project with Emulsion-tRacking Apparatus, CERN CNGS1**

$d = 7.3 \times 10^{7}$cm$= 2.4 \times 10^{-3}$ sec

Delay time = 60.7 ±6.9 ±7.4 [nsec]

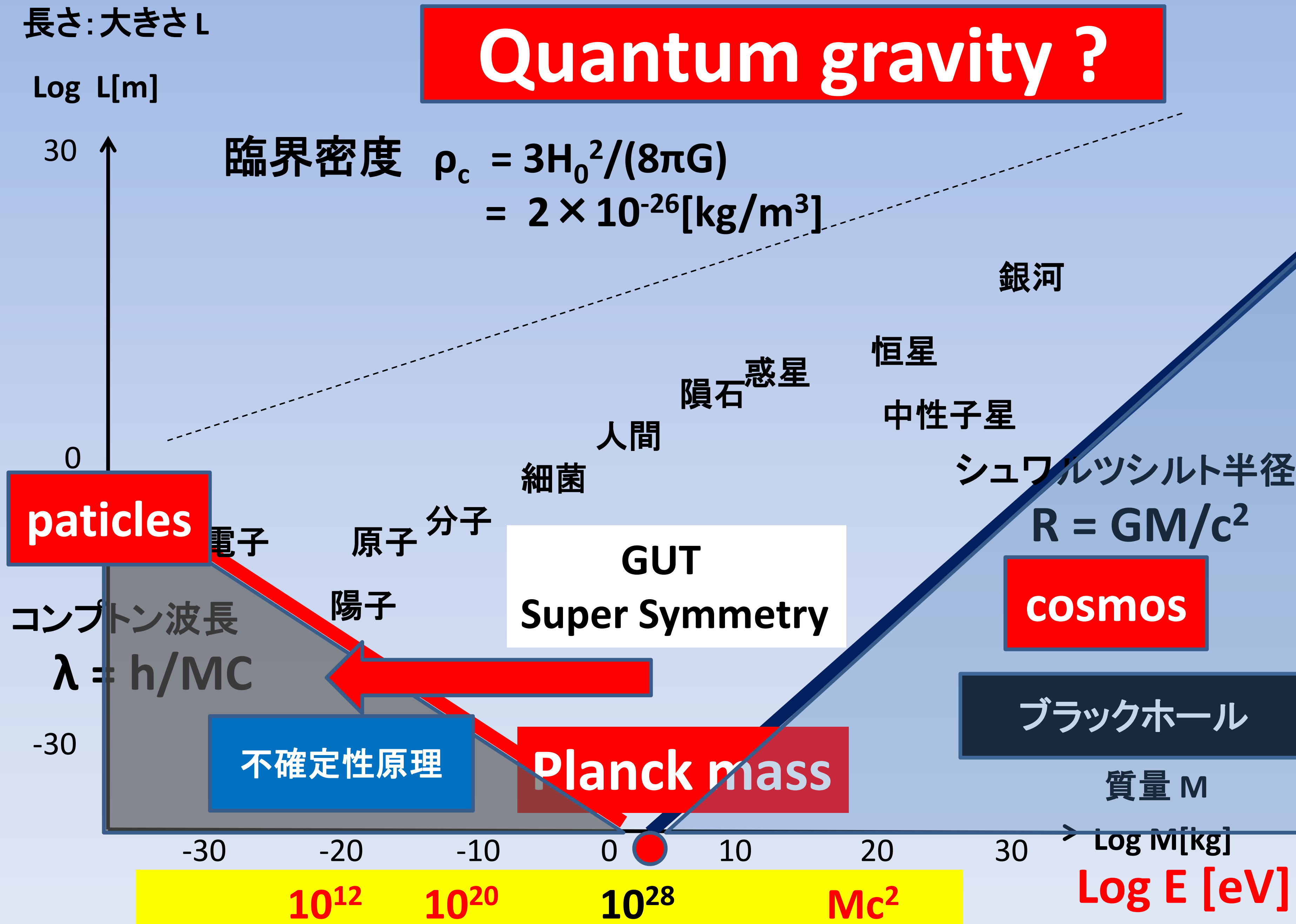
$(v - c)/c = (2.4 \pm 0.28 \pm 0.30) \times 10^{-5}$

相対論（量子重力理論）の高精度検証

emission time within (1-10) second

Emission size within 10^{10-11} cm

宇宙の構成物の大きさ･質量･密度



Effect on propagation speed :

- systematic error ??
- higher gamma ray energy ....

Effects on astrophysical reactions :

yes /no type test/observation

Quantum Gravity effect on VHE gamma ray astrophysics

1. Propagation
2. Emission
3. Detection

$\gamma + \varepsilon\,(\mathrm{EBL}) \rightarrow e^{+} + e^{-}$ absorption

$e + \varepsilon\,(\mathrm{EBL}) \rightarrow e + \gamma$ Inverse Compton

Interaction with atmosphere

$\gamma + A \rightarrow e^{+} + e^{-} + A$

$e + A \rightarrow e + \gamma + A$

A : atmospheric nucleus

Cascade, Air shower process

$$\gamma + \varepsilon\,(\mathrm{EBL}) \rightarrow e^{+} + e^{-}$$

Absorption

Pair creation

$$k_0 - \varepsilon \rightarrow p_+ + p_-$$

$$K_0 + \varepsilon \rightarrow E_+ + E_-$$

$\varepsilon \neq 0$ for the process to proceed

Momentum / energy conservation

Effect of Energy / momentum of EBL photon

?? term of $\xi\, K^2/M_{planck}$??

$\gamma + \varepsilon\ (\text{EBL}) \rightarrow e^{+} + e^{-}$ (absorption)

$\varepsilon \neq 0$ for the process to proceed

$$\text{Energy} : \quad K_0 + \varepsilon = E_1 + E_2$$

$$\text{momentum} : \quad \vec{k}_0 - \vec{\varepsilon} = \vec{p}_1 + \vec{p}_2$$

Relativistic approximation

QG modification

$$k_0 - \varepsilon = K_0 (1 + \xi K/M)^{0.5} - \varepsilon$$

$$p_1 = E_1 (1 - m_e^2/E_1^2 + \xi E_1/M)^{0.5}$$

$$p_2 = E_2 (1 - m_e^2/E_2^2 + \xi E_2/M)^{0.5}$$

Threshold energy, phase volume, ...

$\gamma + \varepsilon\ (EBL) \rightarrow e^{+} + e^{-}$

Perpendicular component

$$K_0 - \varepsilon + \xi K_0^2/(2M)$$

$$= p_1 + p_2 - p_1\,\theta_1^2/2 - p_2\,\theta_2^2/2$$

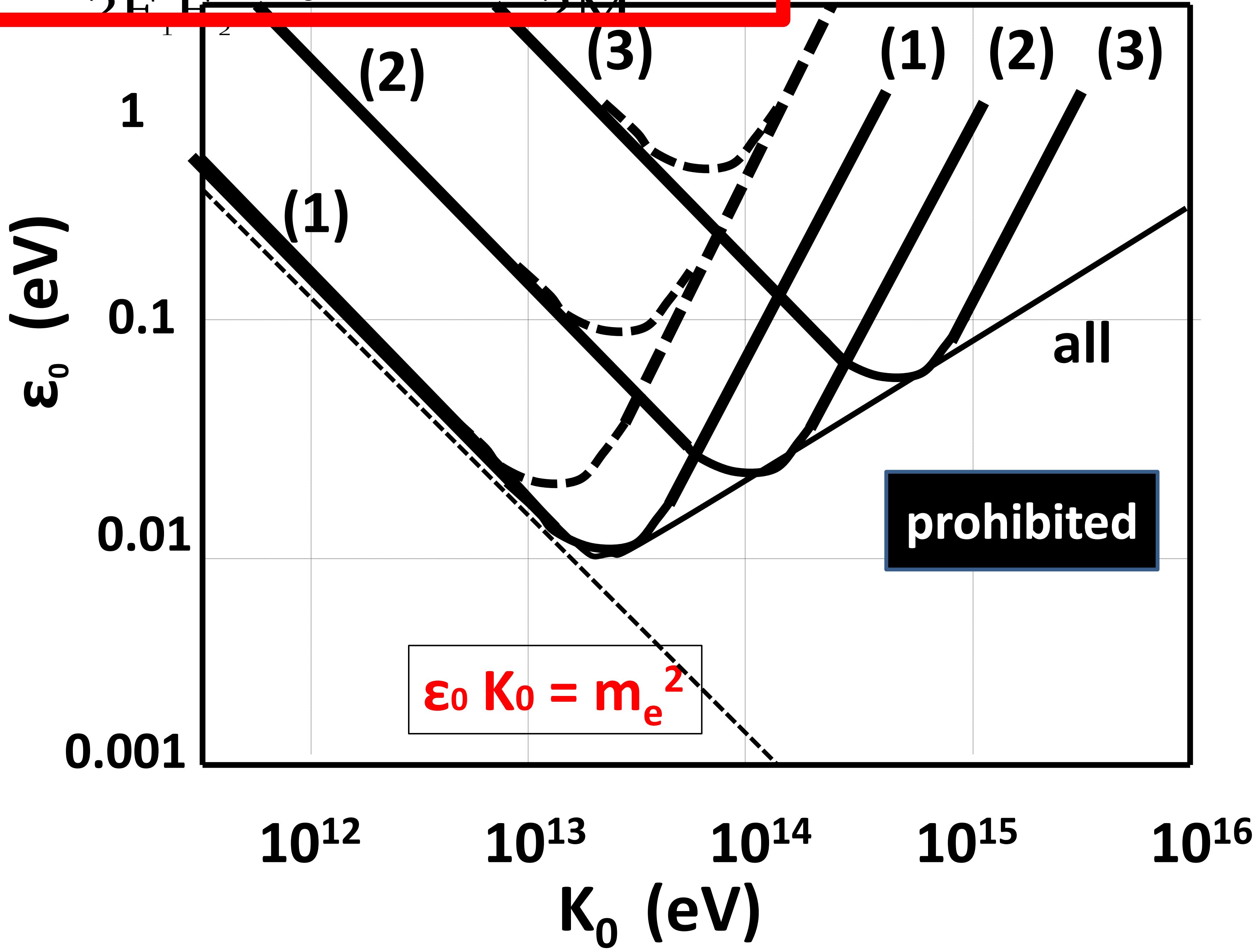
$$< p_1 + p_2$$

$$< E_1 + E_2 - Km^2/(2E_1E_2)$$

$$+\xi(E_1^2+E_1^2)/(2M)$$

$$\boxed{2\varepsilon > \frac{K_0}{2E_1E_2} m_e^2 + \xi \frac{K_0^2 - E_1^2 - E_2^2}{2M}}$$

$$2\varepsilon > \frac{K_0}{2E_1E_2} m_e^2 + \xi \frac{K_0^2 - E_1^2 - E_2^2}{2M}$$



$$4\varepsilon > \frac{1}{K_0 a(1-a)} m_e^2 + \xi \frac{K_0^2 \cdot 2a(1-a)}{M}$$

$$a = \frac{E_1}{K_0}$$

$$1 - a = \frac{E_2}{K_0} = \frac{K_0 - E_1}{K_0}$$

左辺 ＞ 右辺第1項	threshold
左辺 ＞ 右辺第2項	prohibition /suppression of large K_0
右辺第1項 ≈ 右辺第2項	characteristic energy “asymmetric parameter “a

characteristic /critical energies

$$\varepsilon_c = \left(\frac{m_e^4}{M}\right)^{1/3} \approx 10^{-2}\,\mathrm{eV}$$

Infra Red

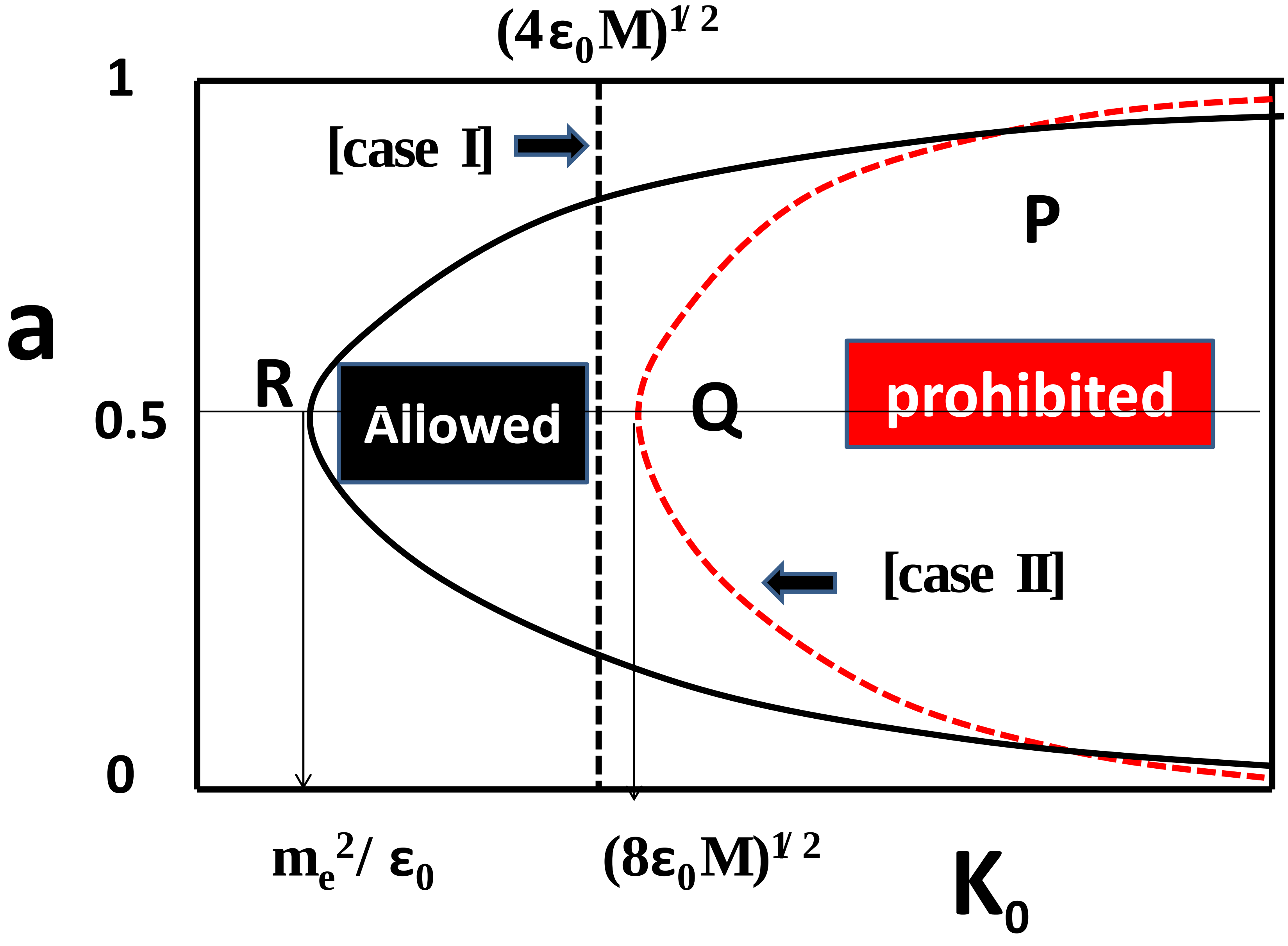
x

$$K_c = (m_e^2 M)^{1/3} \approx 10^{13}\,\mathrm{eV}$$

10-100 TeV

$$K_* = (\varepsilon M)^{1/2} \approx \frac{\varepsilon}{1\,\mathrm{eV}} \cdot 10^{14}\,\mathrm{eV}$$

$\gamma + \varepsilon\,(EBL) \rightarrow e^{+} + e^{-}$



Inverse Compton scattering

$e + \varepsilon\,(\mathrm{EBL}) \rightarrow e + \gamma$

momentum : $\vec{p}_0 - \vec{\varepsilon} = \vec{p} + \vec{k}$

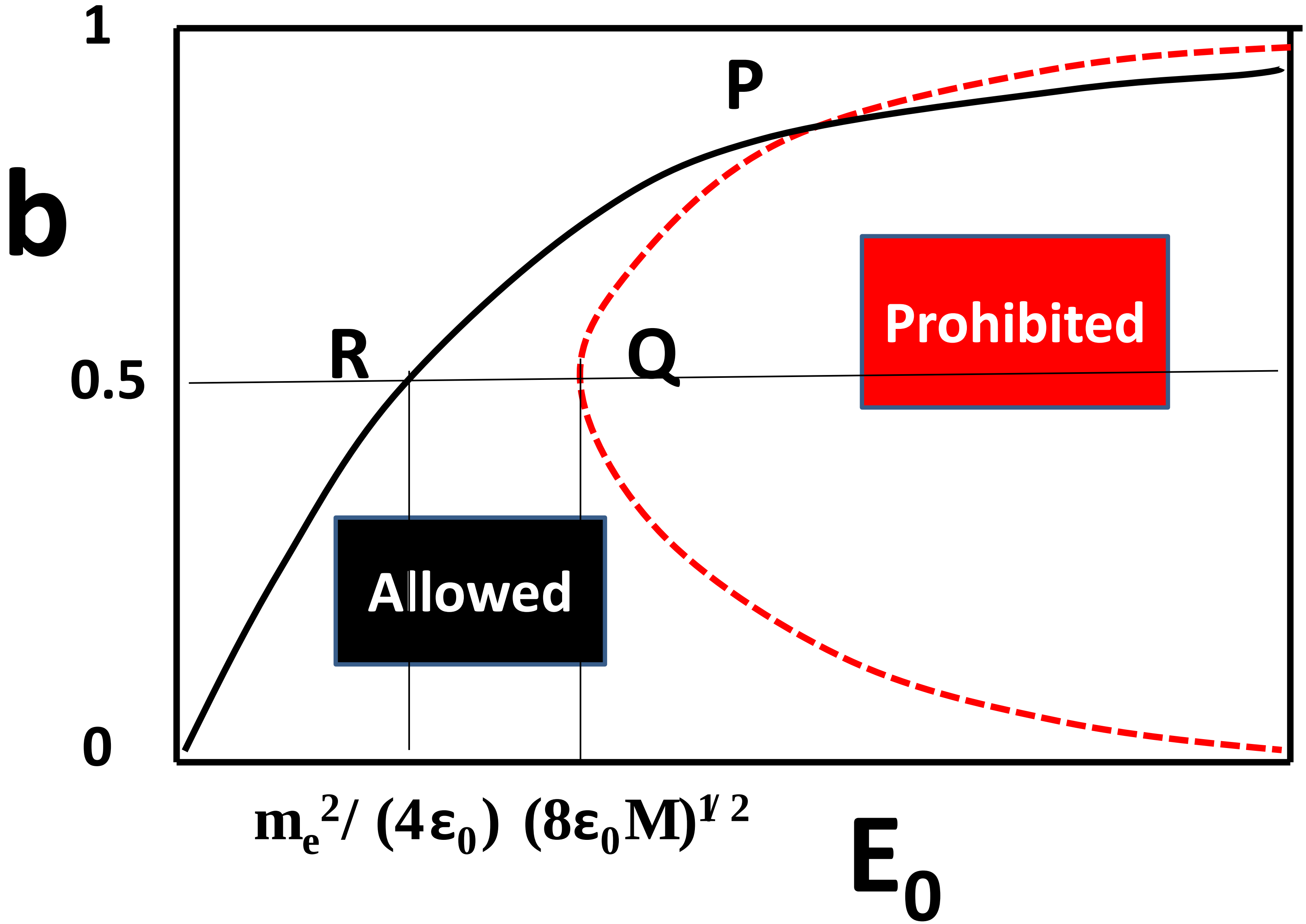
Energy : $E_0 + \varepsilon = E + K$

$$2\varepsilon > \frac{K}{2E_0E} m_e^2 + \xi \frac{E_0^2 - E^2 - K^2}{2M}$$

$$2\varepsilon > \frac{b}{2E_0(1-b)} m_e^2 + \xi \frac{E_0^2 \cdot b(1-b)}{M}$$

$b = K/E_0$

$e + \varepsilon\,(EBL) \rightarrow e + \gamma$



IC/synchrotron radiation

$e + \varepsilon\,(\mathrm{EBL}) \rightarrow e + \gamma$

$$\boxed{\boxed{2\varepsilon > \frac{K}{2E_0 E} m_e^2} + \xi \frac{E_0^2 - E^2 - K^2}{2M}}$$

$b = K/E_0$

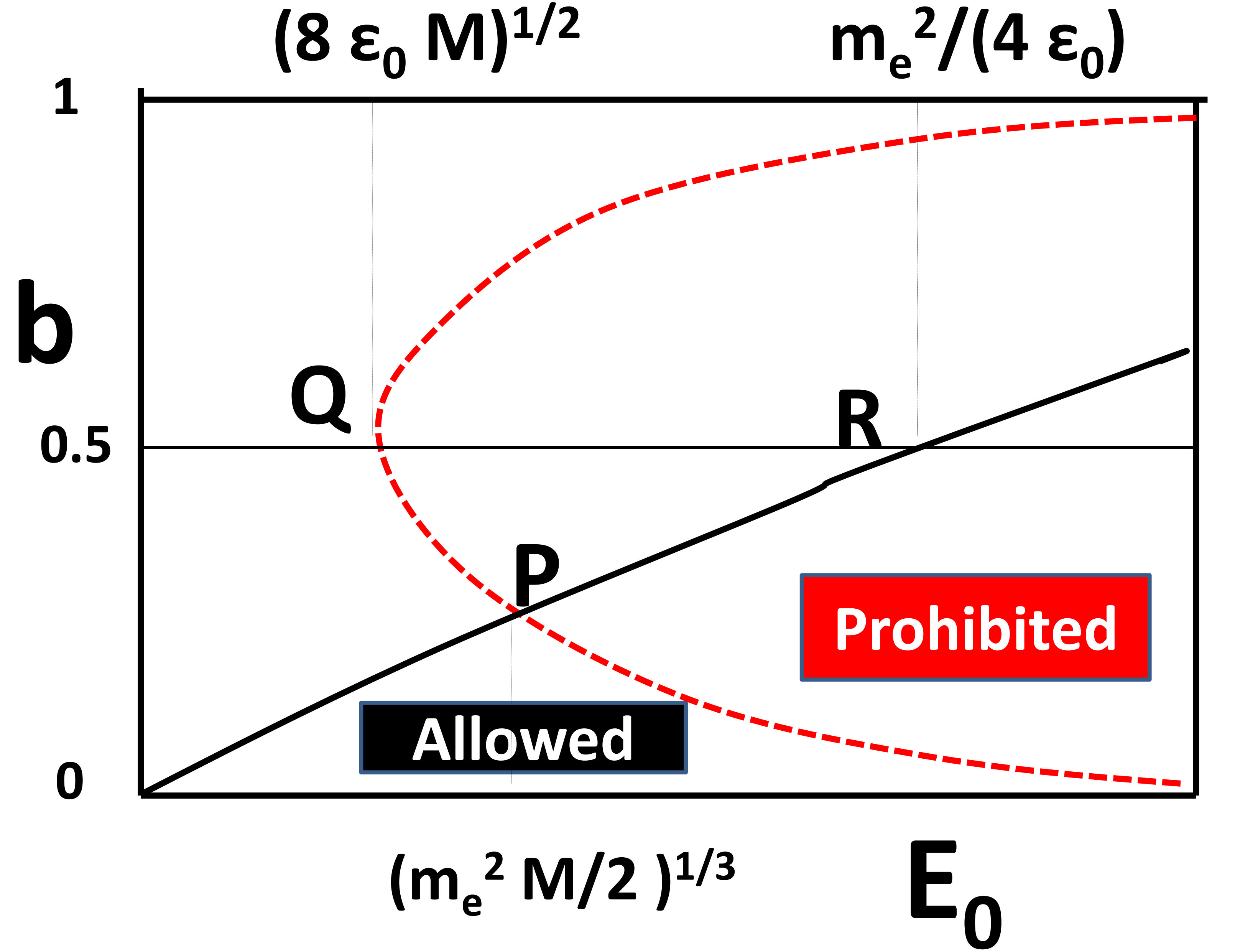
$$2\varepsilon > \frac{b}{2E_0(1-b)} m_e^2 + \xi \frac{E_0^2 \cdot b(1-b)}{M}$$

$$\boxed{K < \frac{4\varepsilon E_0}{m_e^2 + 4\varepsilon E_0} E_0 \approx \frac{4\varepsilon E_0^2}{m_e^2}}$$

$$\boxed{K < 4\varepsilon\left(\frac{E_o}{m_e}\right)^2 \cdot \frac{1}{1 + \frac{2E_0^3}{m_e^2 M}}}$$

e + ε (EBL) → e+ γ

synchrotron radiation



Effects on interaction/process

- Prohibition of reaction

$$(\varepsilon M)^{1/2}$$

- Suppression

$$(m_e{}^2 M)^{1/3}$$

- **Asymmetric energy partition for final particles**

Asymmetric energy partition

$\gamma + \varepsilon\,(\mathrm{EBL}) \rightarrow e^- + e^+$

$a = E_1/K_0$

$A = 1/(a(1-a))$

$$4K_0\varepsilon > Am_e^2 + \xi\frac{K_0^2}{M}$$

Left > 1 st or 2 nd term of right side

$$\frac{A}{4\varepsilon}m_e^2 < K_0 < \sqrt{4\varepsilon M}$$

$$\frac{A}{4\varepsilon}m_e^2 < K_0 < \sqrt{2\varepsilon AM}$$

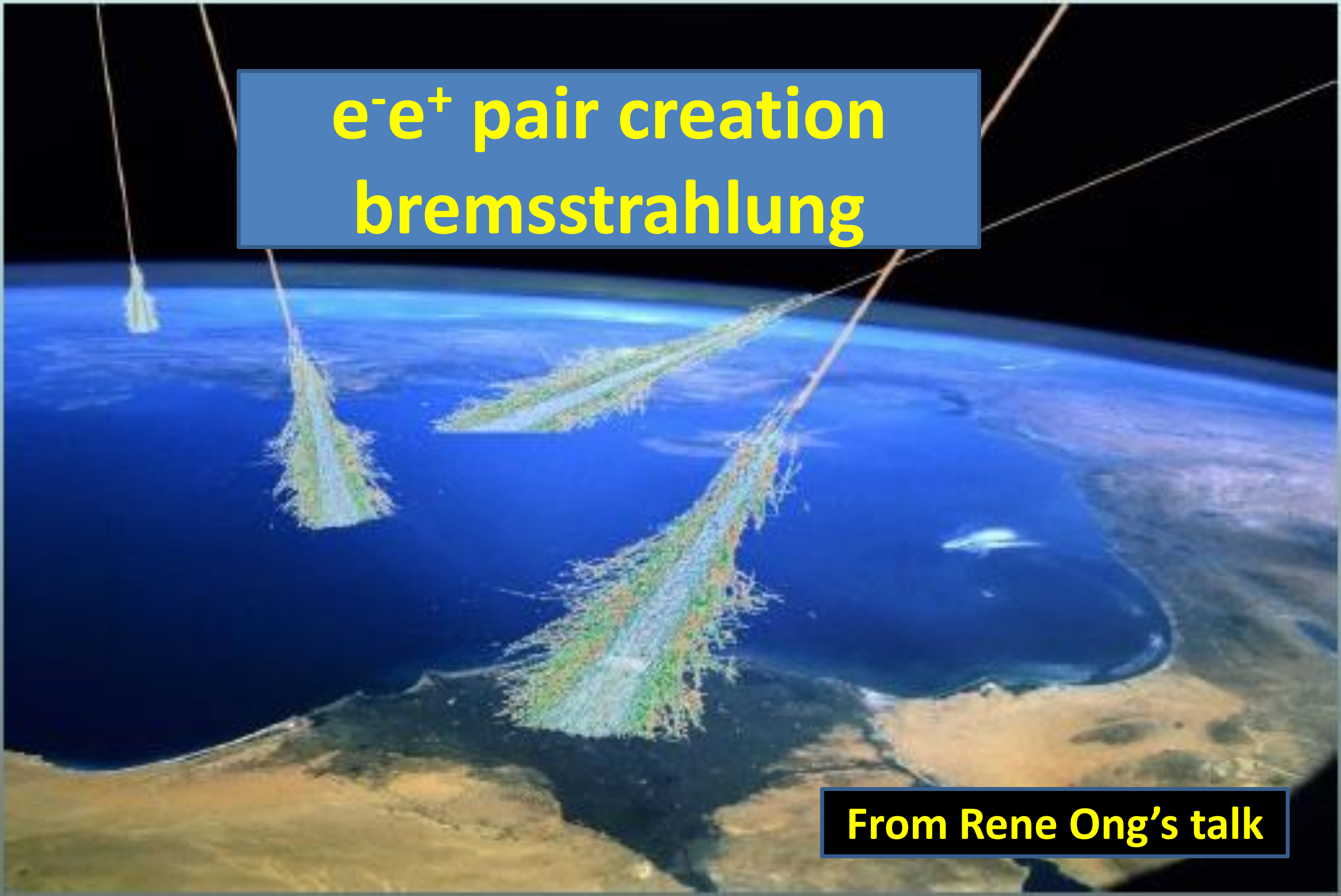
$$\frac{K_0^2}{2\varepsilon M} < A < \frac{2\varepsilon^3 M}{m_e^4}$$

1 st ¥ge 2 nd term of right side

$$A > \frac{K_0^3}{m_e^2 M} = 0.4\cdot\left(\frac{K_0}{10^{13}}\right)^3$$

$$A > \sqrt{\frac{2K_0^3}{m_e^2 M}} = 0.9\cdot\left(\frac{K_0}{10^{13}}\right)^{3/2}$$

Extensive Air Showers



$\gamma + \gamma_b \text{(EBL)} \rightarrow e^+ + e^-$

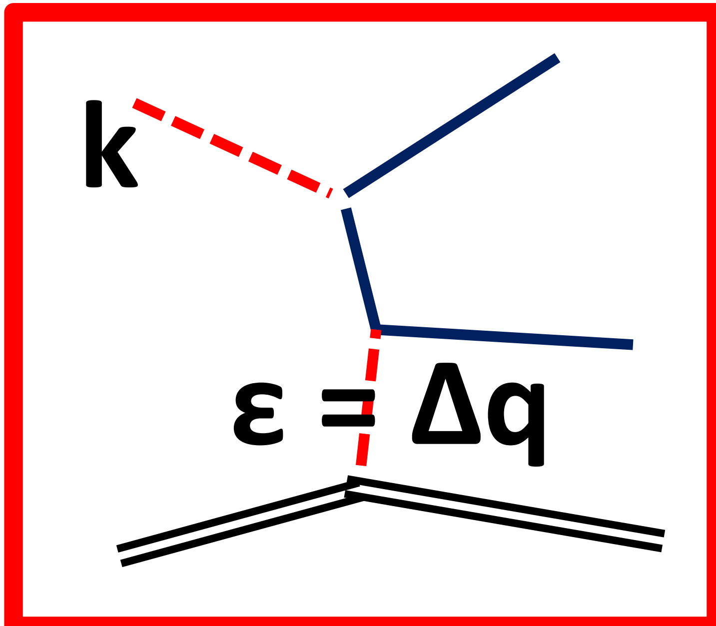
momentum : $\vec{k} - \vec{\varepsilon} = \vec{p}_1 + \vec{p}_2$

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

momentum : $\vec{k} = \vec{p}_1 + \vec{p}_2 + \vec{\Delta q}$

$\varepsilon \rightarrow \Delta q$

$$\Delta q > \frac{K_0}{2E_1E_2} m_e^2 + \xi \frac{K_0^2 - E_1^2 - E_2^2}{2M}$$



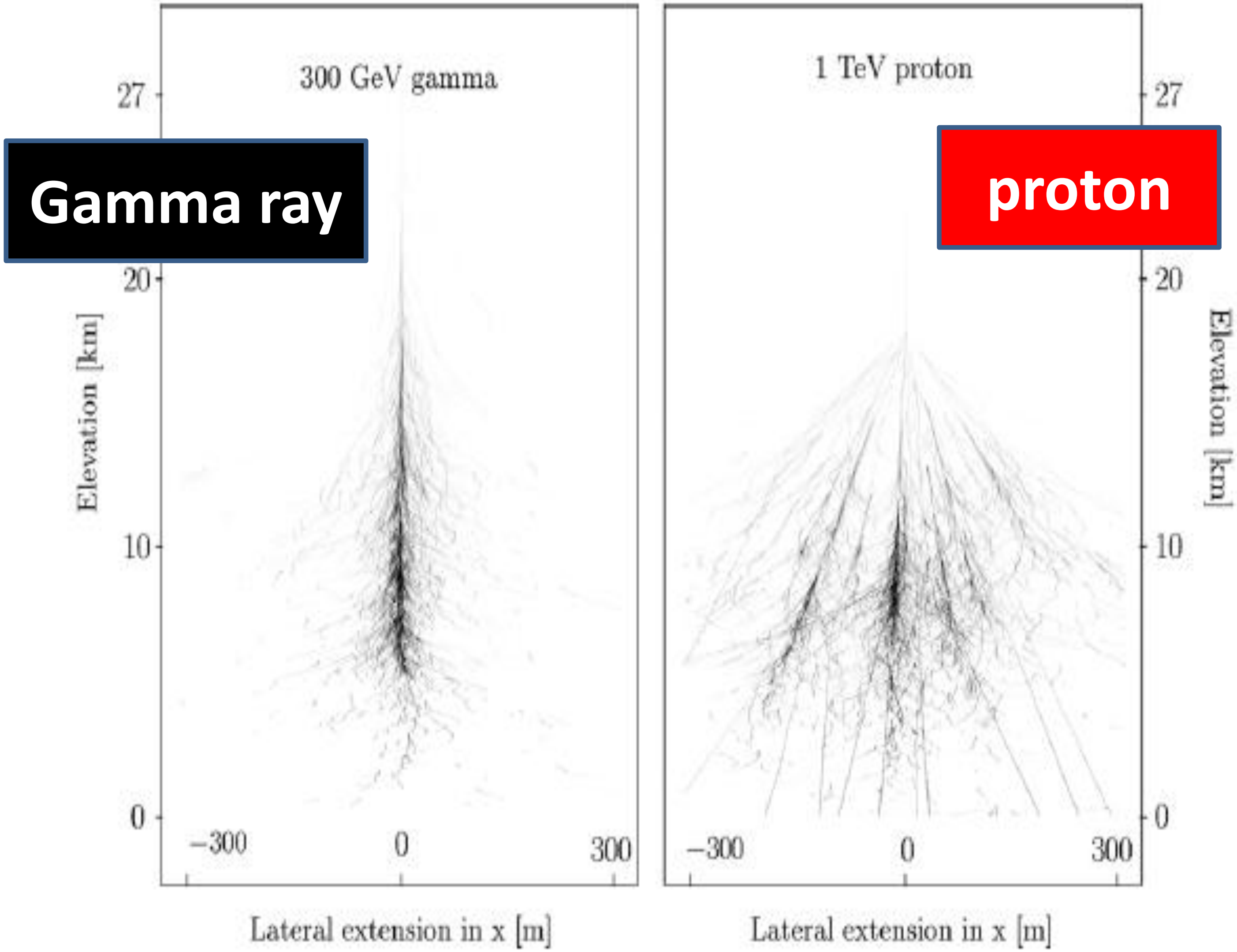
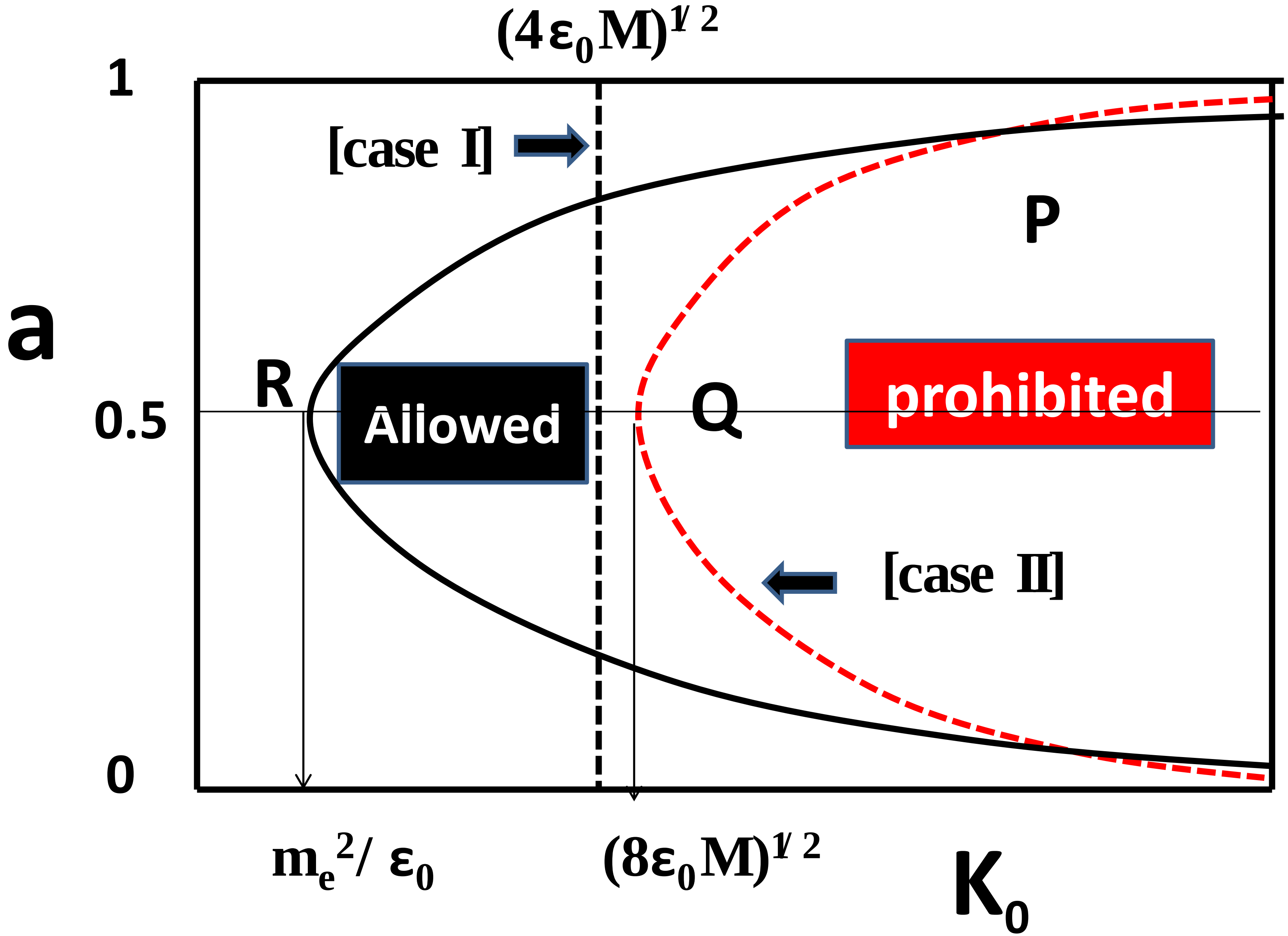
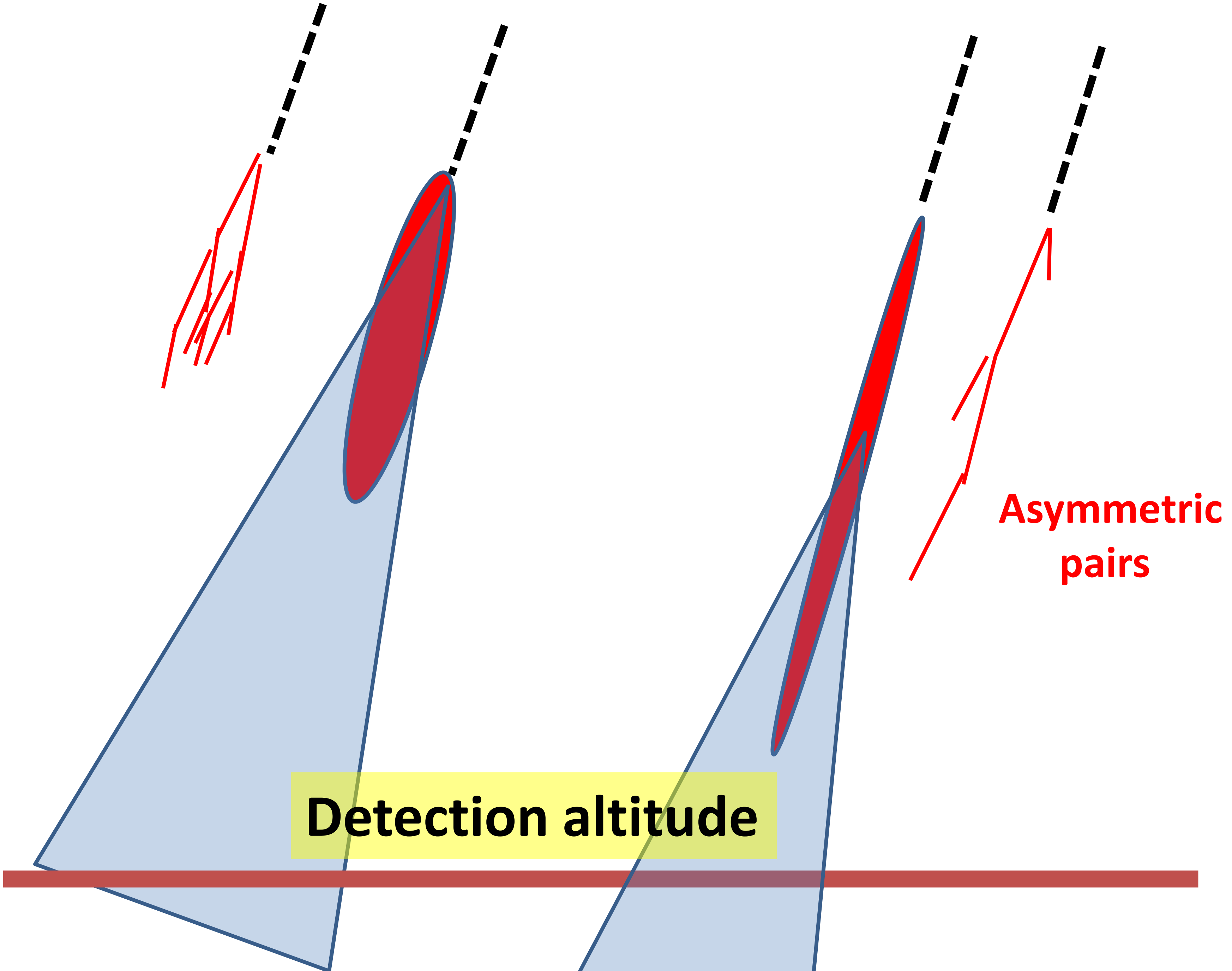


Figure 7. Comparison of a pure electromagnetic shower (from a 300 GeV γ ray) and a hadronic shower (initiated by a 1 TeV proton). The plot shows the projection of secondary particle trajectories onto an (x, z) plane (courtesy of Stefan Funk).

$\gamma + \varepsilon\,(EBL) \rightarrow e^{+} + e^{-}$




Asymmetric
pairs
Detection altitude

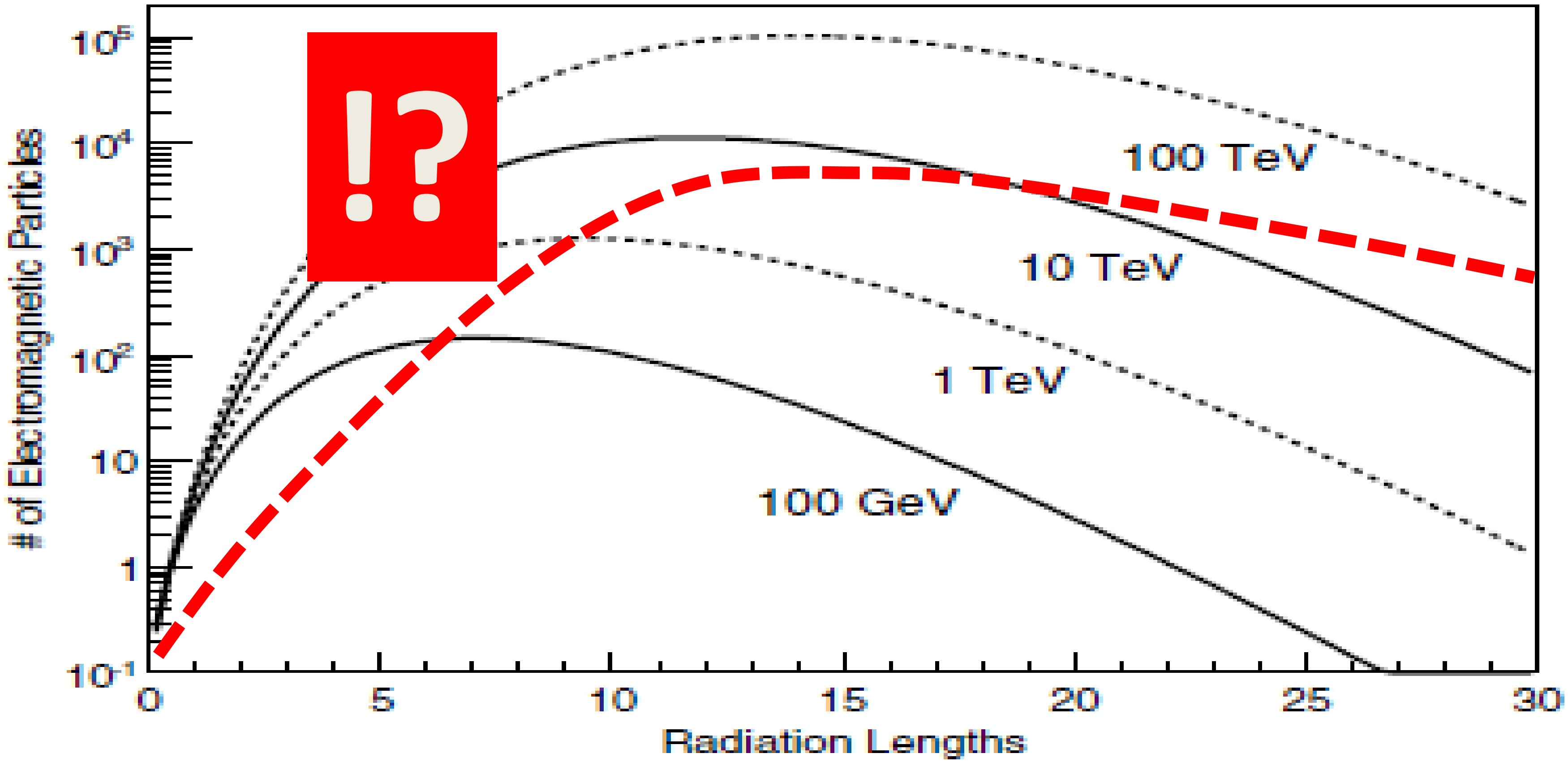


Figure 4. The longitudinal development of an extensive air shower as given by approximation B for several different primary gamma ray energies. The x-axis is the atmospheric depth expressed as the number of radiation lengths. The y-axis gives the number of electromagnetic particles in the air shower. Sea level is ~28 radiation lengths of atmosphere, 2600 m above sea level is ~20 radiation lengths, 4300 m above sea level is ~16.5 radiation lengths and 5200 m above sea level is ~14.7 radiation lengths.

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

The case of all particles are relativistic

momentum : $\vec{k} = \vec{p}_1 + \vec{p}_2 + \vec{p}_A$

$$2K_0 m_A > \frac{K_0(K_0 - E_A)}{E_1 E_2} m_e^2 + \frac{K_0}{E_A} m_A^2 + \xi \frac{K_0^2 - E_1^2 - E_2^2 - E_A^2}{2M}$$

$E_1 \rightarrow K_0$

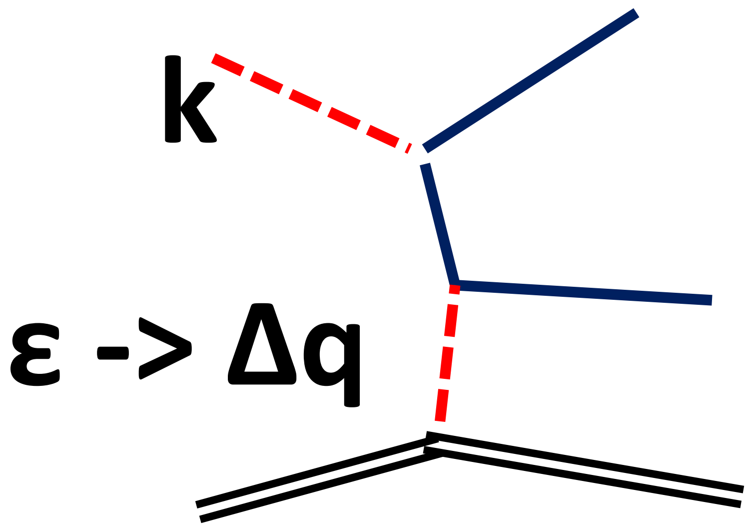
or

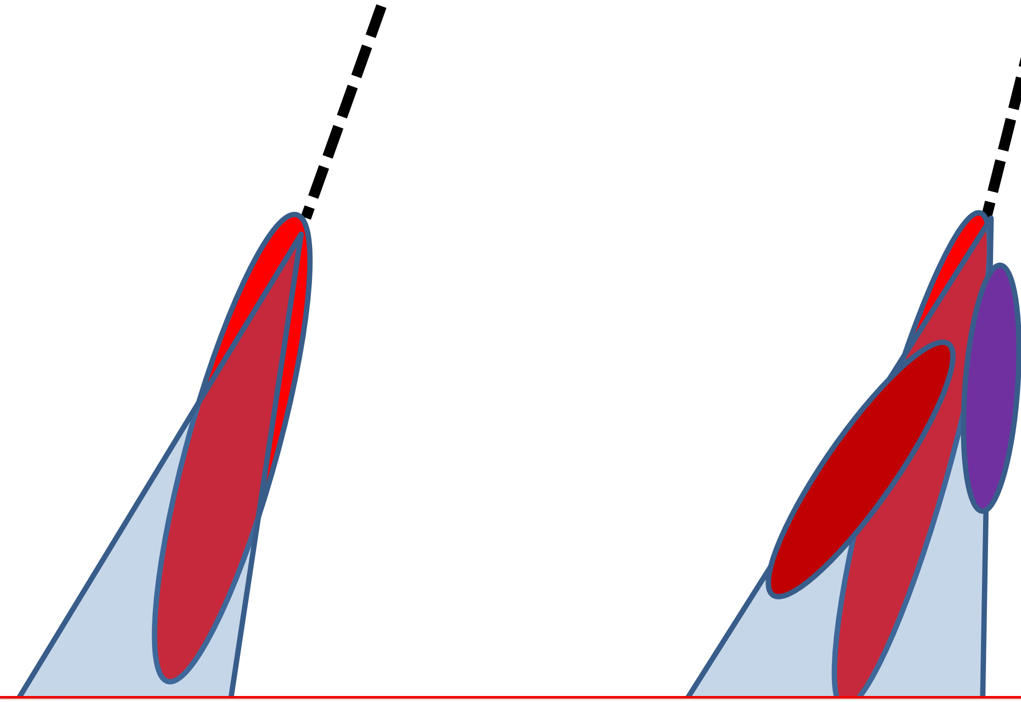
$E_2 \rightarrow K_0$

or

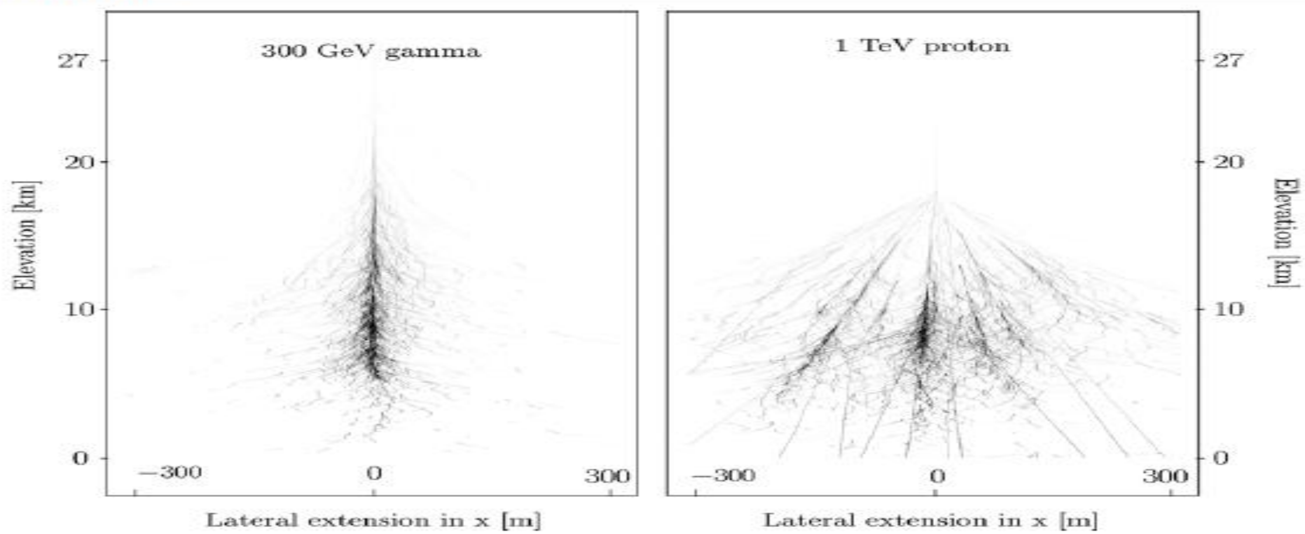
$E_A \rightarrow K_0$

favored





Rep. Prog. Phys. **71** (2008) 096901 — F Aharonian *et al*



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Gamma-ray initiated Extensive Air Shower ?

- **Slow development of EAS**

  Penetrating deeper to the bottom of atmosphere

- **High altitudes ←--→ sea level ?**

  At least, it is necessary to compare the results at different altitudes

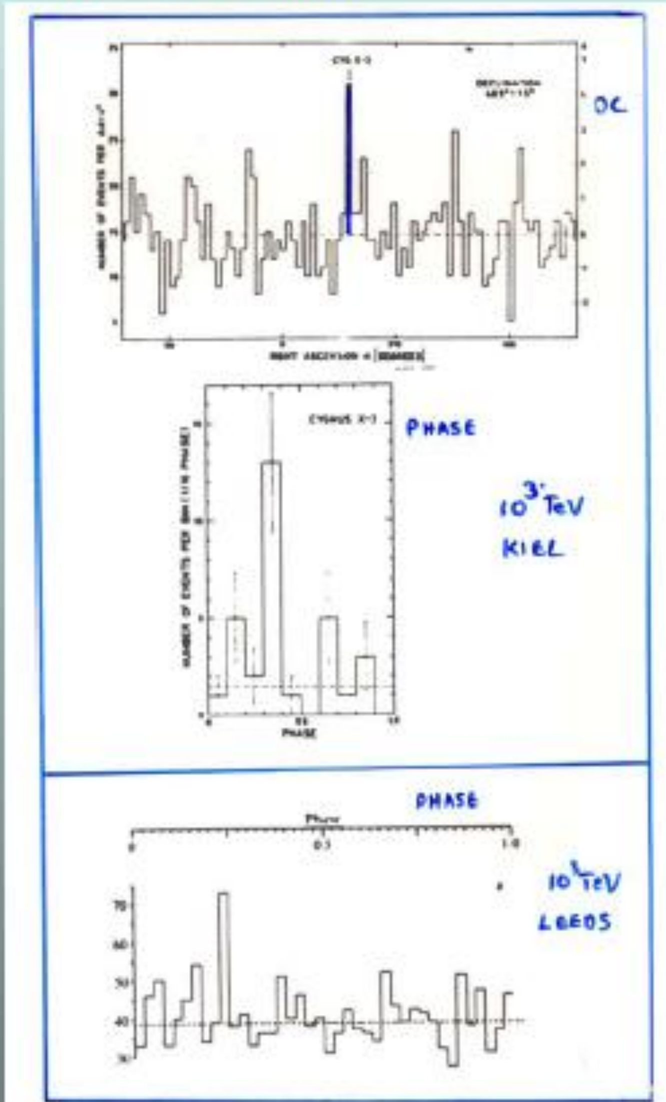
- **Proton-like shower…….**

  muon content ?

  width, concentration …….

Cygnus X-3

Results 1983



Crimea

Experiment Details

Kiel Experiment:
claim 4.4σ signal.

28 counters, each 1 m^2
Energy: 1-10 PeV

4.8 hr periodicity

Not muon poor !?

Time variable
Recently detected by Fermi

Haverah Park
~ 4σ effect.

4 large water Cherenkov detectors.
Energy > 1 PeV

Adding some words onto a slide from Rene Ong's

summary

- Extragalactic gamma ray of $10^{14} – 10^{15}$ eV

  We badly need

  clear evidence for quantum gravity effect

  \- gamma rays from nearby galaxies ←→ CR physics

- Suppression of IC, synchrotron radiation

  for $E_0 > 10^{13} – 10^{14}$ eV

  → SSC model lepton/hadron model.. ..

- **Detection method ?**

  Are we driving a right vehicle

  along the paved road / right road ?

  toward the destination we are heading for ?

- Many other effects ....
- Prospect for gamma ray astronomy/CR physics

  will be dramatically changed