Particle Acceleration in Gamma-ray Bursts

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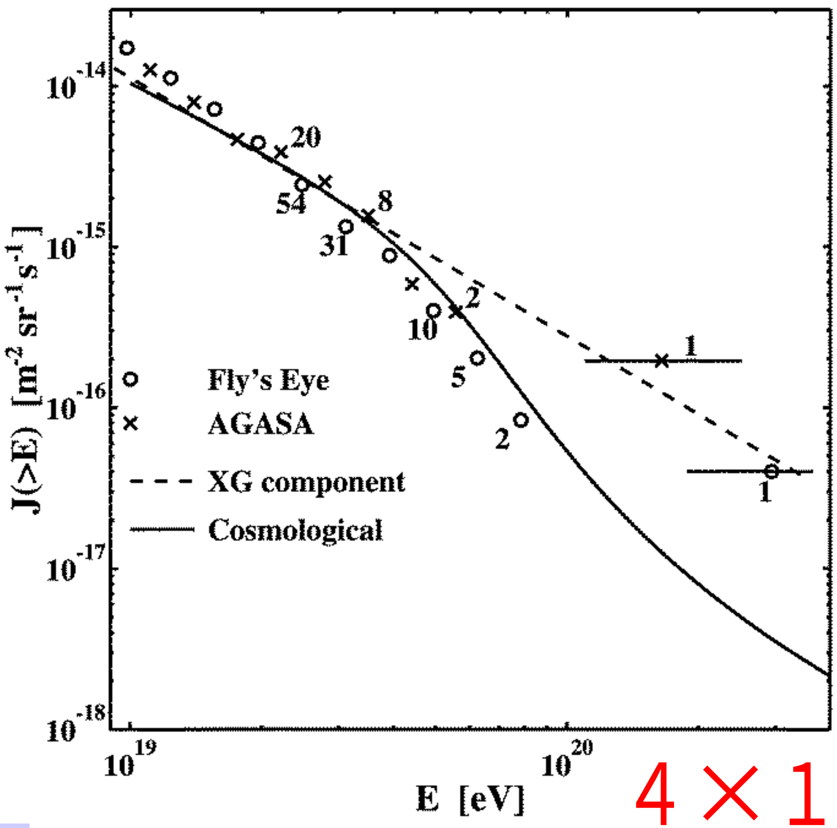
Ultra High-Energy Cosmic Rays (UHECR)

- Gamma-ray Burst (GRB) is a candidate of UHECR ($>10^{19}$eV) source.



Waxman 1995

If the total energy of accelerated protons above 10^{19}eV in GRBs is comparable to the gamma-ray energies, it can explain the flux of UHECRs.

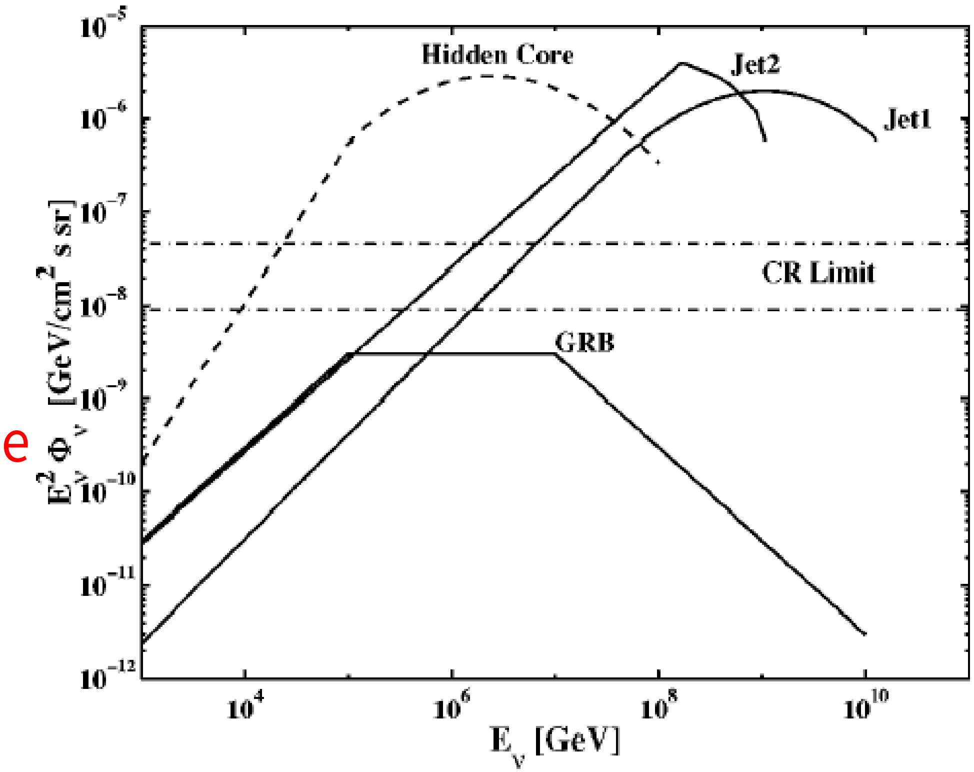
4×10^{44} erg Mpc^{-3} yr^{-1}

Neutrino Burst

$$p + \gamma \rightarrow n + \pi^+$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$



- High energy nucleons create pions so that neutrino bursts may occur.

Waxman and Bahcall 1997, 1998

Problems

- If high-energy nucleons create too much pions, they lose their energies before escape.
- In actual GRBs, do accelerated pions create too much pions?
- Both neutrino burst and UHECR production occurs at the same time in a GRB?

Pion Production

- Photon density in a shell is determined by its luminosity.
- The dynamical time scale is determined by the width of the shell.
- In Waxman and Bahcall (1997)

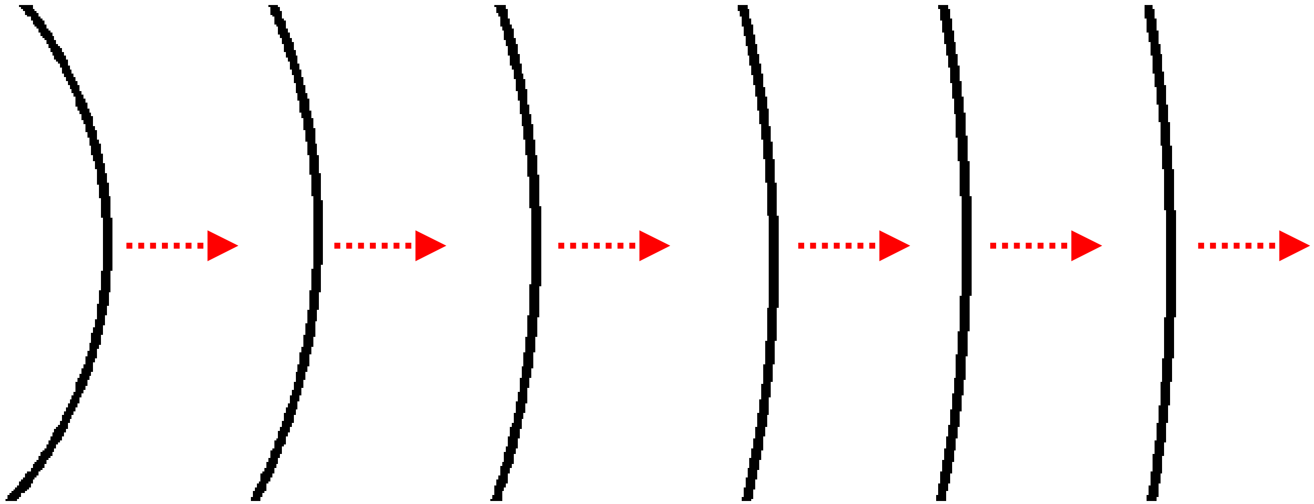
$$L \sim 10^{51} \mathrm{erg/s},\ \Delta t \sim 1 \mathrm{msec}$$

$$\longrightarrow\ E \sim 10^{48} \mathrm{erg}$$

Monte-Carlo Simulation

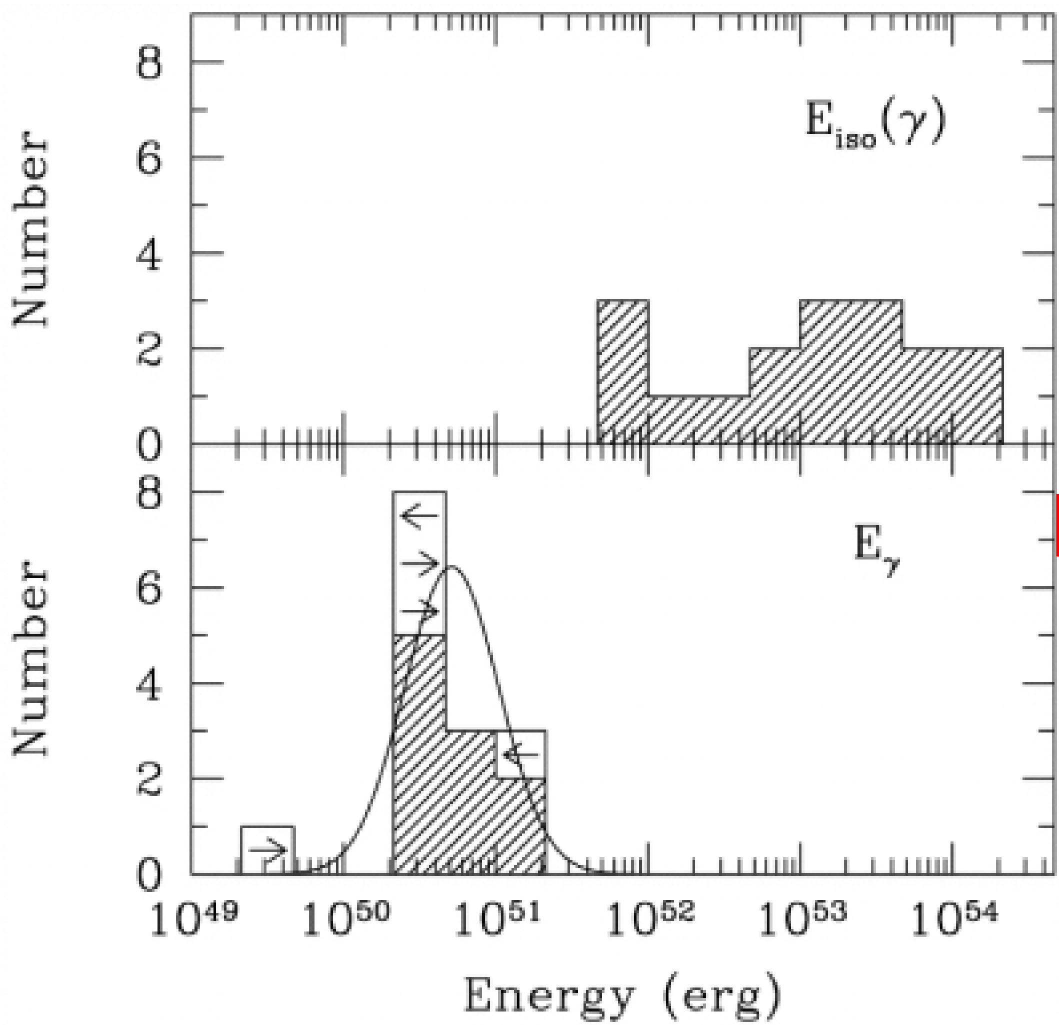
- I follow energy-loss processes of each nucleon in GRB photon field by the Monte-Carlo Simulation.
- Resultant neutrino and photon emission are obtained
  - Synchrotron
  - Inverse Compton

How Many Photons in a Shell?



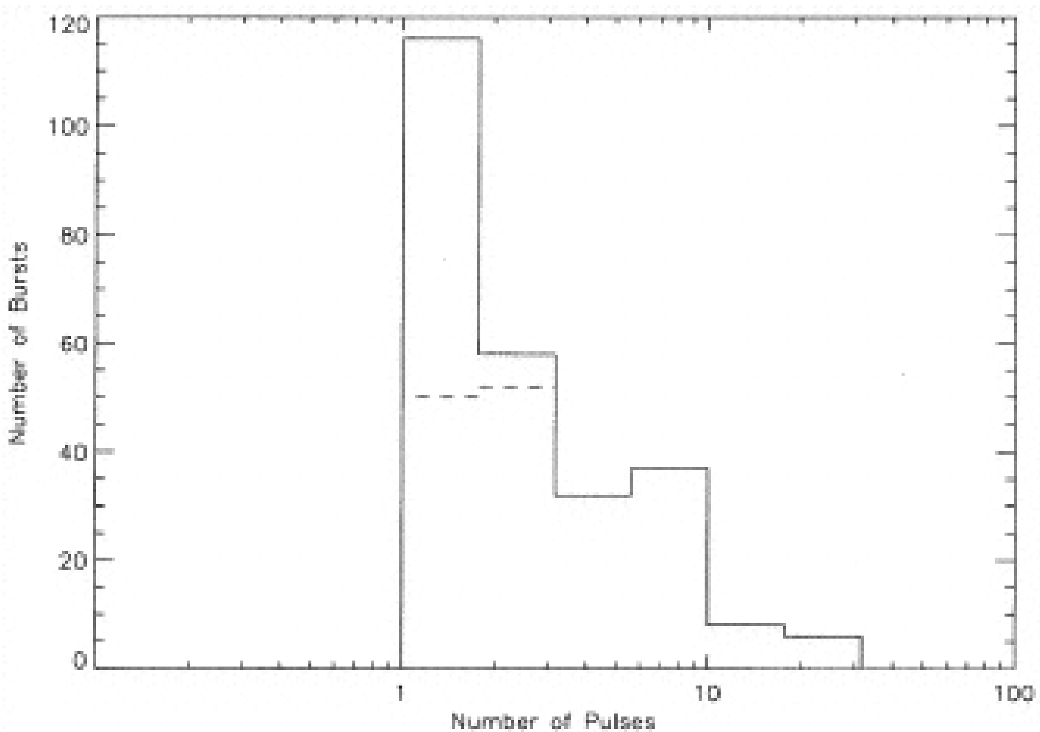
Gamma-rays are emitted from multiple shells with high Lorentz factor.

Total Energy



$E>10^{52}$erg

Energy per Shell



$E>10^{51}$erg

The number of pulses in a GRB<10

Shell Width

Variability Time Scale：＞1msec

Duration time：＜10sec

Lorentz Factor：＞100

↓

Shell width in the Comoving frame

We assume $l = 10^{10}$-10^{14}cm.

Physical Parameter

$U = E / (4\pi \Gamma R^2 l)$

R: radius where photons are emitted

As an optimistic case,

$E = 10^{51}$ erg $\Gamma = 300$

Energy density of magnetic field $U_B = 0.1U$

GRB photon field

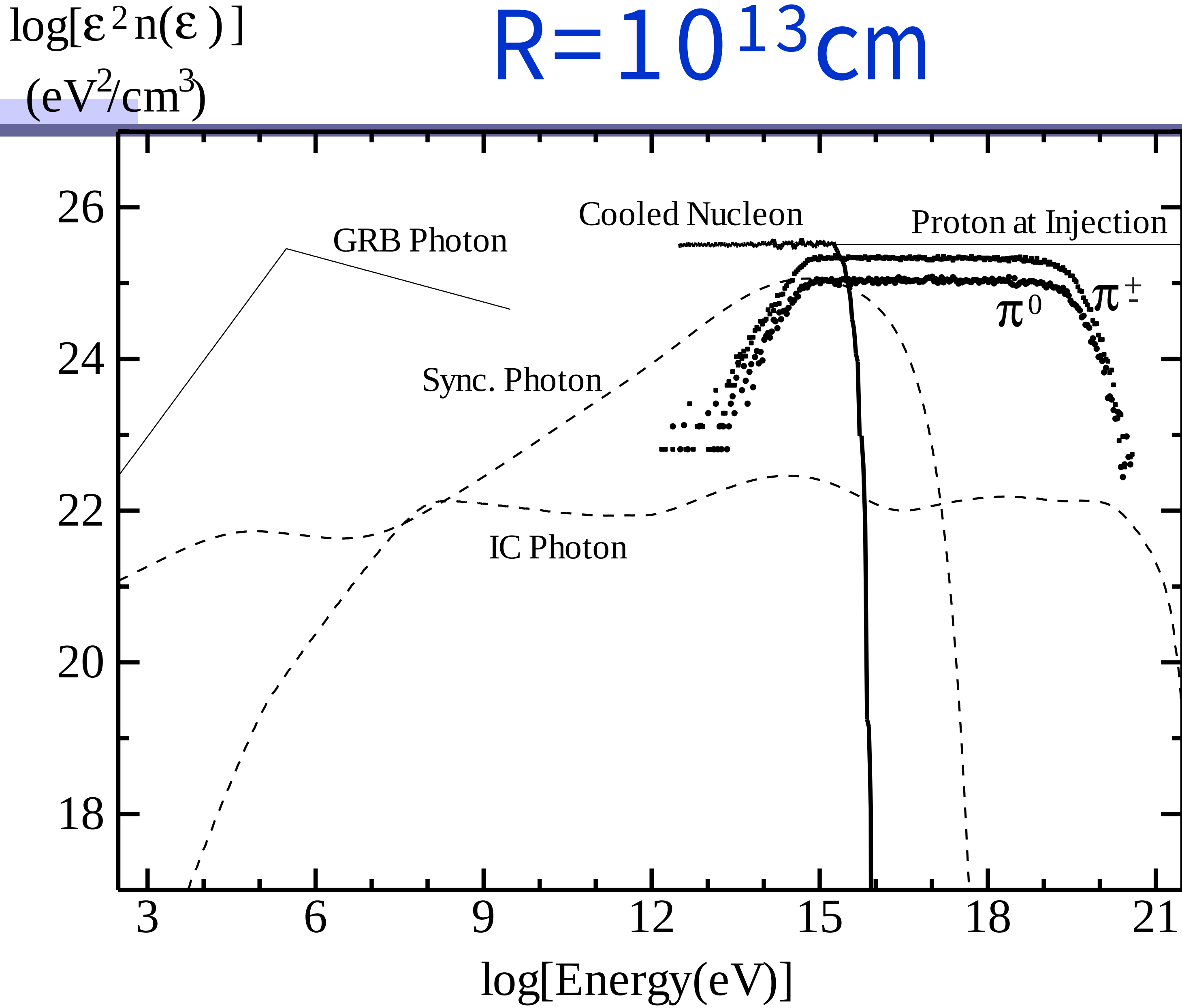
$n(\varepsilon) \propto \varepsilon^{-1}$ for $1\ \mathrm{eV} < \varepsilon < 1\ \mathrm{keV}$

$n(\varepsilon) \propto \varepsilon^{-2.2}$ for $1\ \mathrm{keV} < \varepsilon < 10\ \mathrm{MeV}$

Cooling Processes of UHECRs

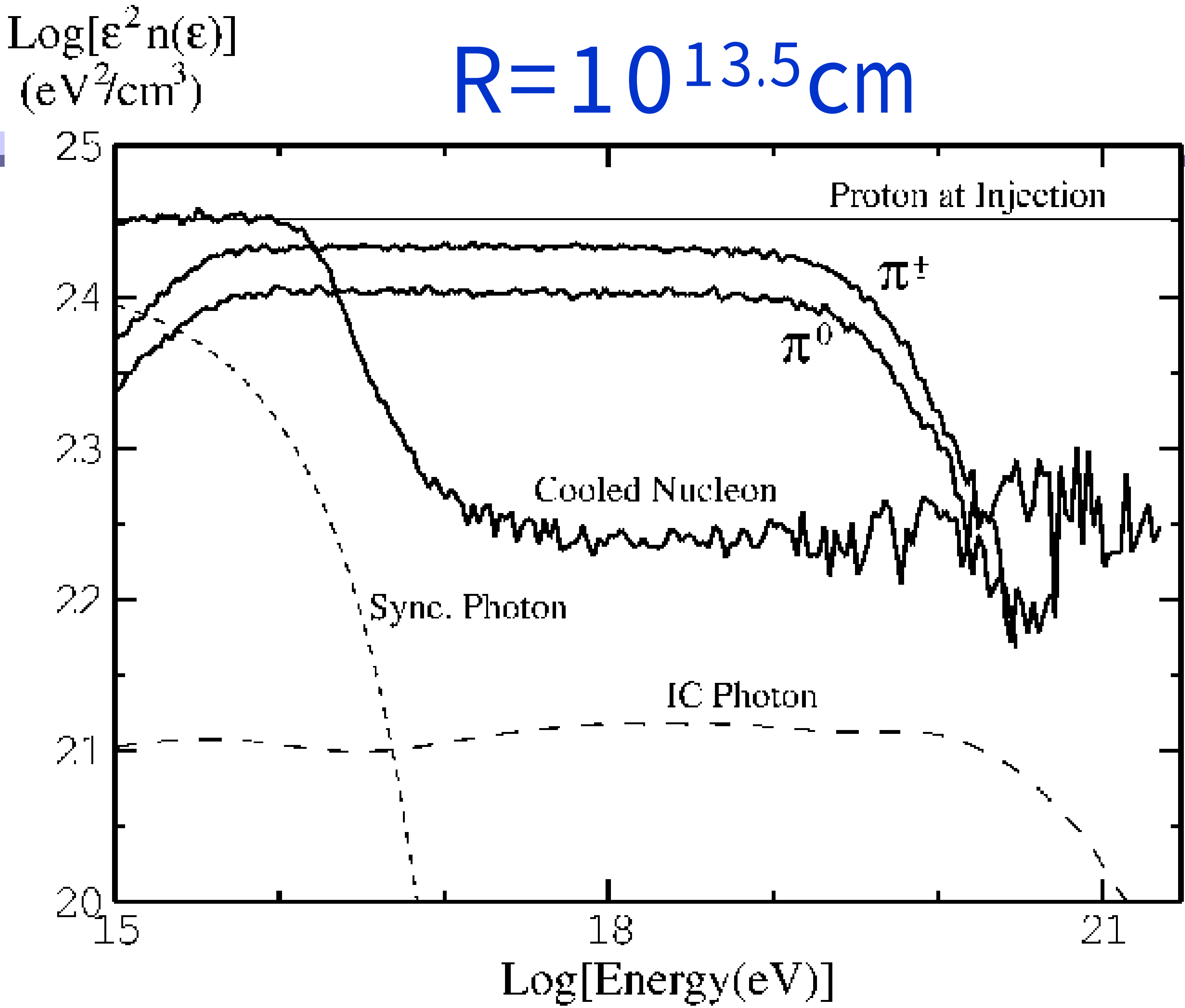
- During the dynamical time scale l/c, UHECRs interact photons.
- The Cooling Time Scale $\propto R^2 l$.
- As a result, the cooling efficiency is independent of the shell width l.
- The results depend on only R.

$R=10^{13}$cm



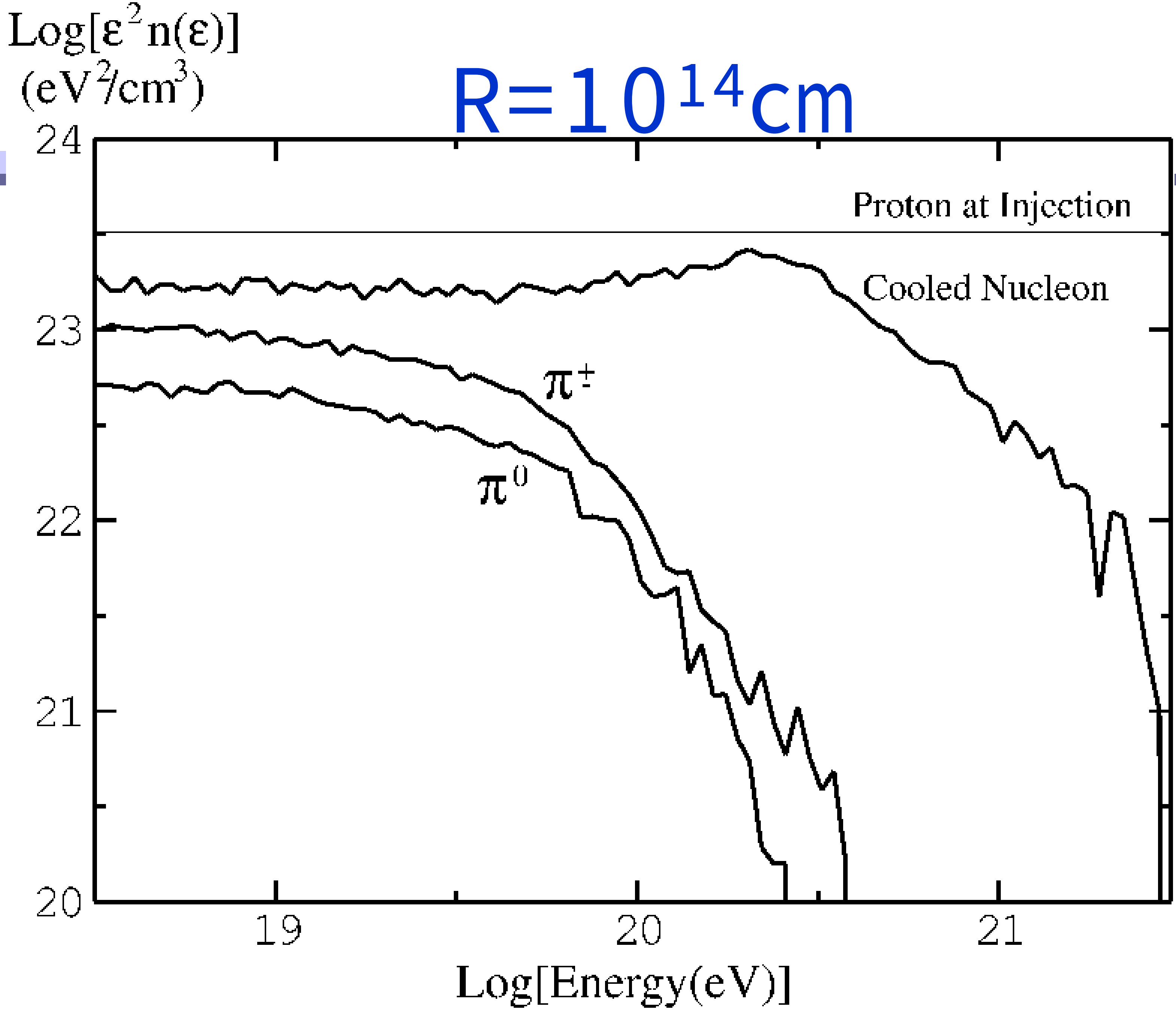
log[ε 2 n(ε)]
(eV2/cm3)
26
24
22
20
18
3
6
9
12
15
18
21
log[Energy(eV)]
GRB Photon
Cooled Nucleon
Proton at Injection
π 0
π ±
Sync. Photon
IC Photon

$R=10^{13.5}$cm



Log[ε²n(ε)]
(eV²/cm³)
25
24
23
22
21
20
15
18
21
Log[Energy(eV)]
Proton at Injection
π±
π0
Cooled Nucleon
Sync. Photon
IC Photon

$R=10^{14}$cm

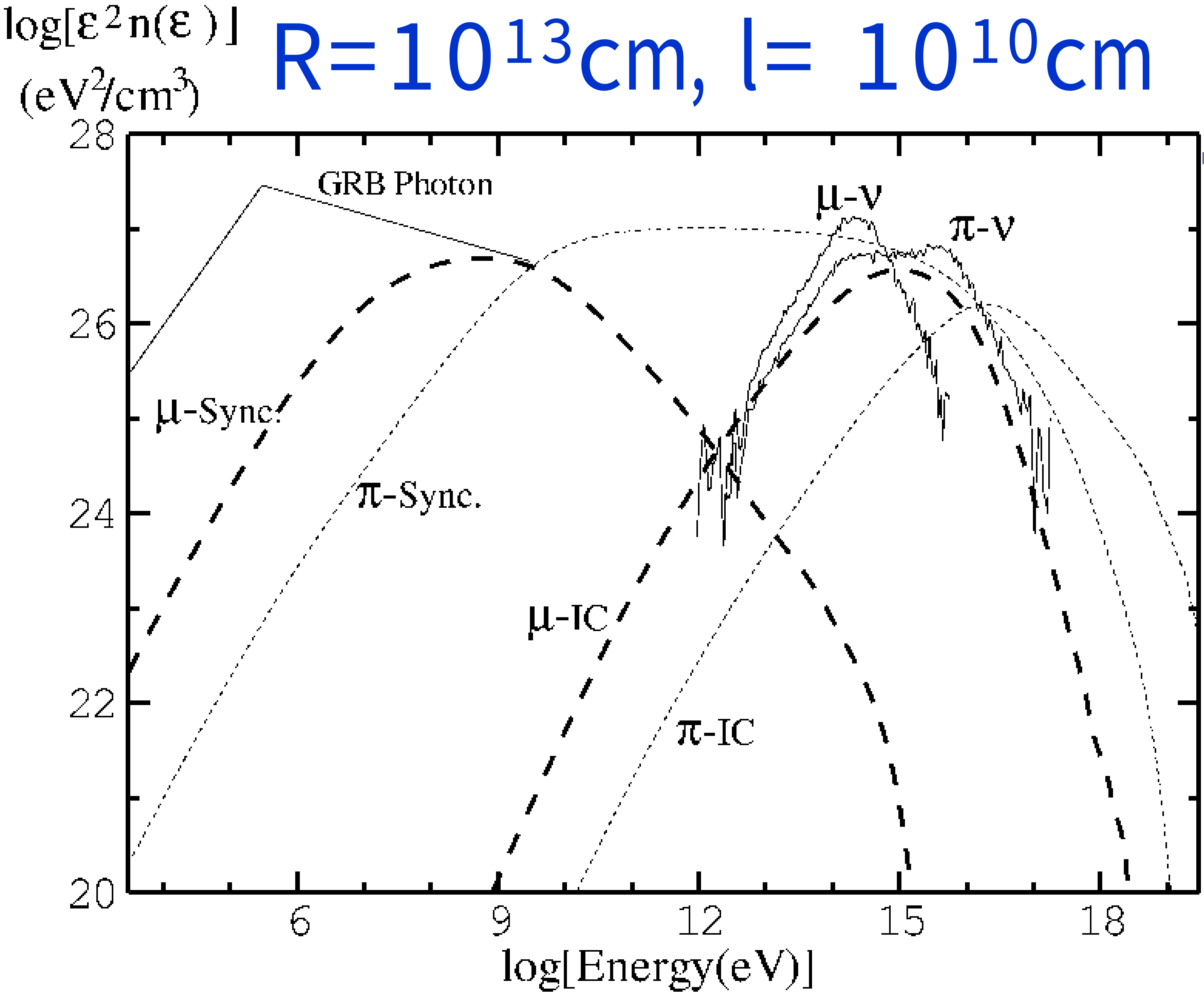


Log[ε²n(ε)]
(eV²/cm³)
24
23
22
21
20
19
20
21
Proton at Injection
Cooled Nucleon
π±
π0
Log[Energy(eV)]

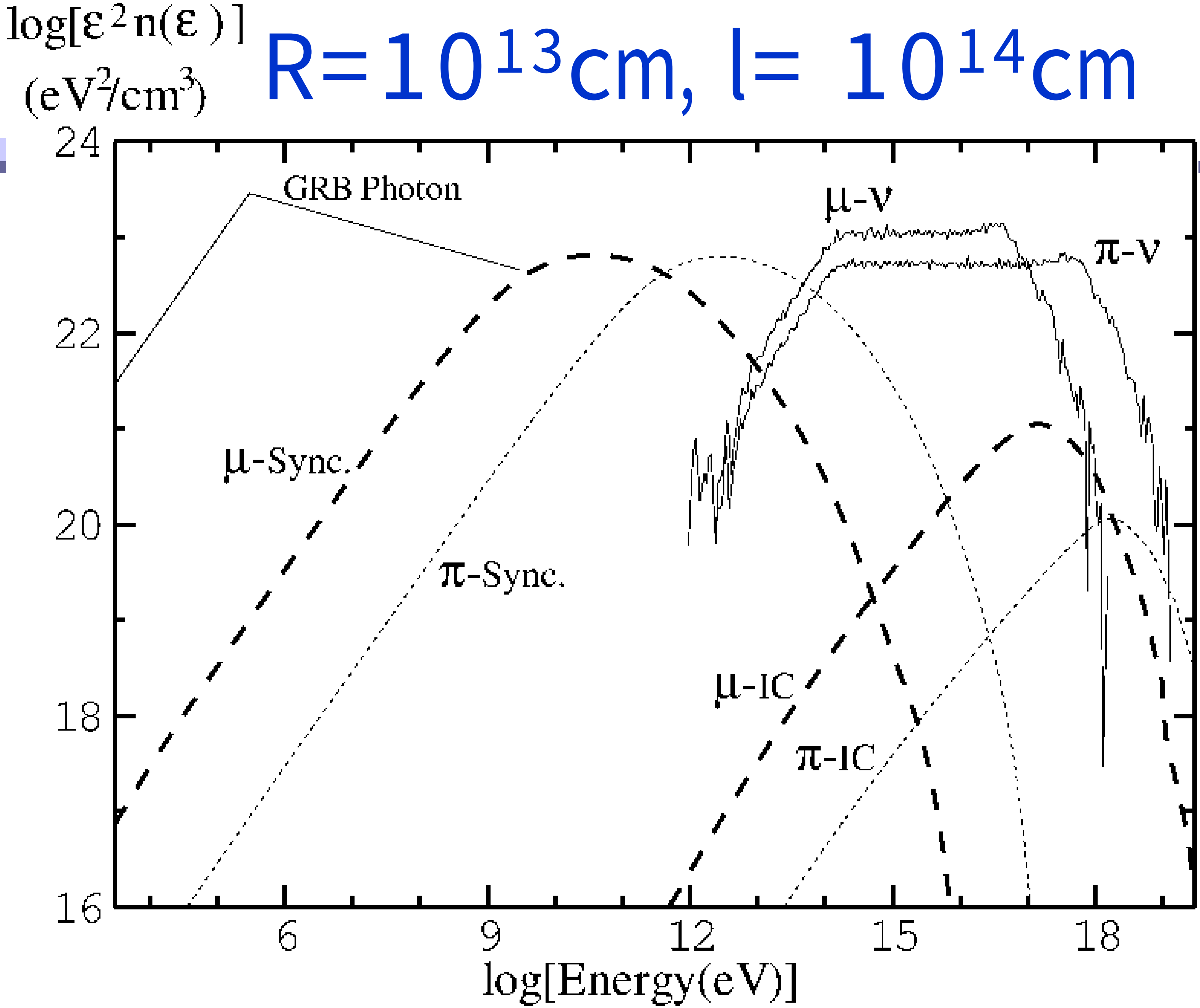
Energy Fraction

R(cm)	Nucleon	Pion	Photon
10^{13}	0.33	0.57	0.10
$10^{13.5}$	0.43	0.47	0.10
10^{14}	0.73	0.19	0.08
$10^{14.5}$	0.94	0.03	0.03
10^{15}	0.99	0.002	0.01

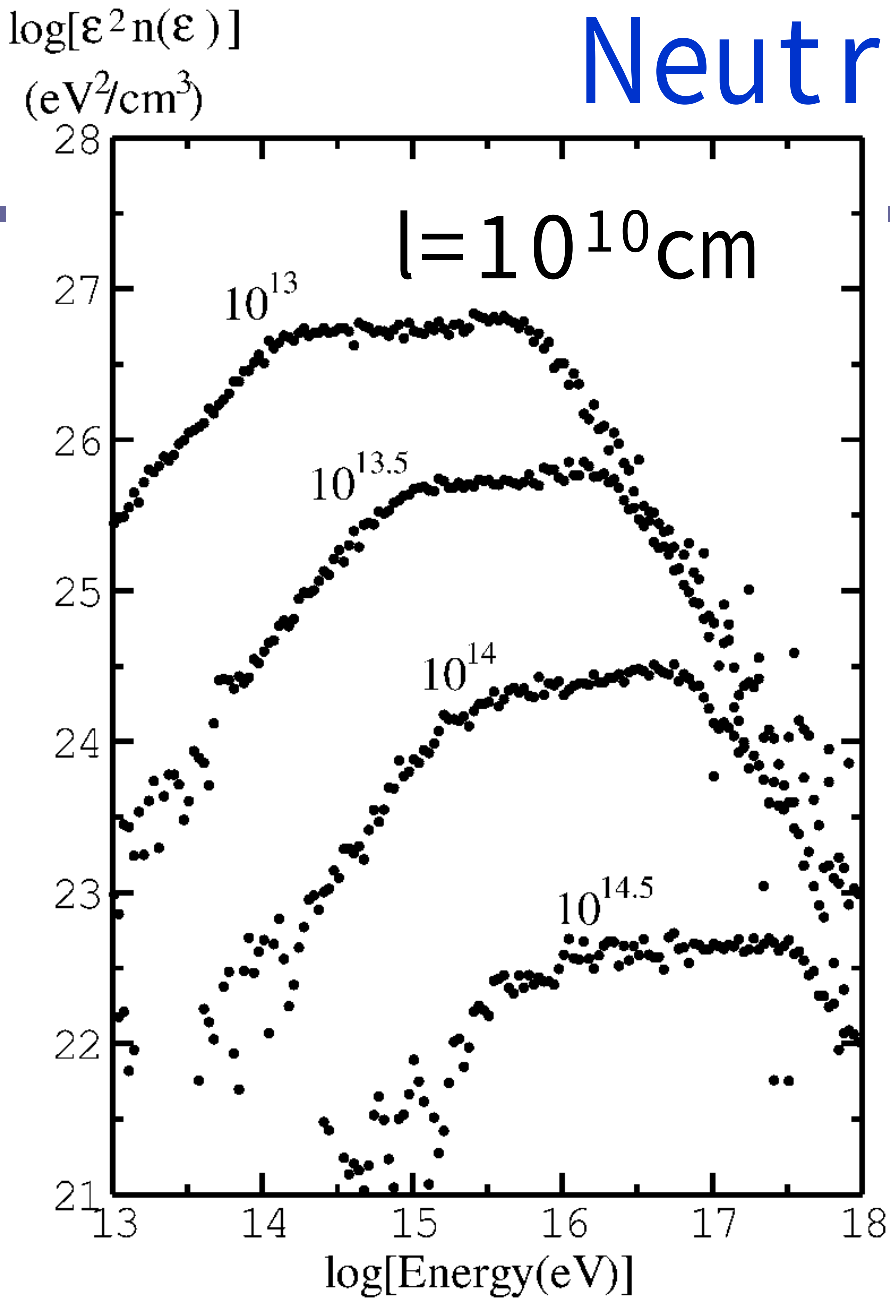
$R=10^{13}$cm, $l= 10^{10}$cm



$R=10^{13}$cm, $l= 10^{14}$cm



Neutrino Spectra



High-energy cut-off is determined by the life time and cooling time of pions.
Low-energy cut-off is determined by the minimum energy of pions produced from nucleons.

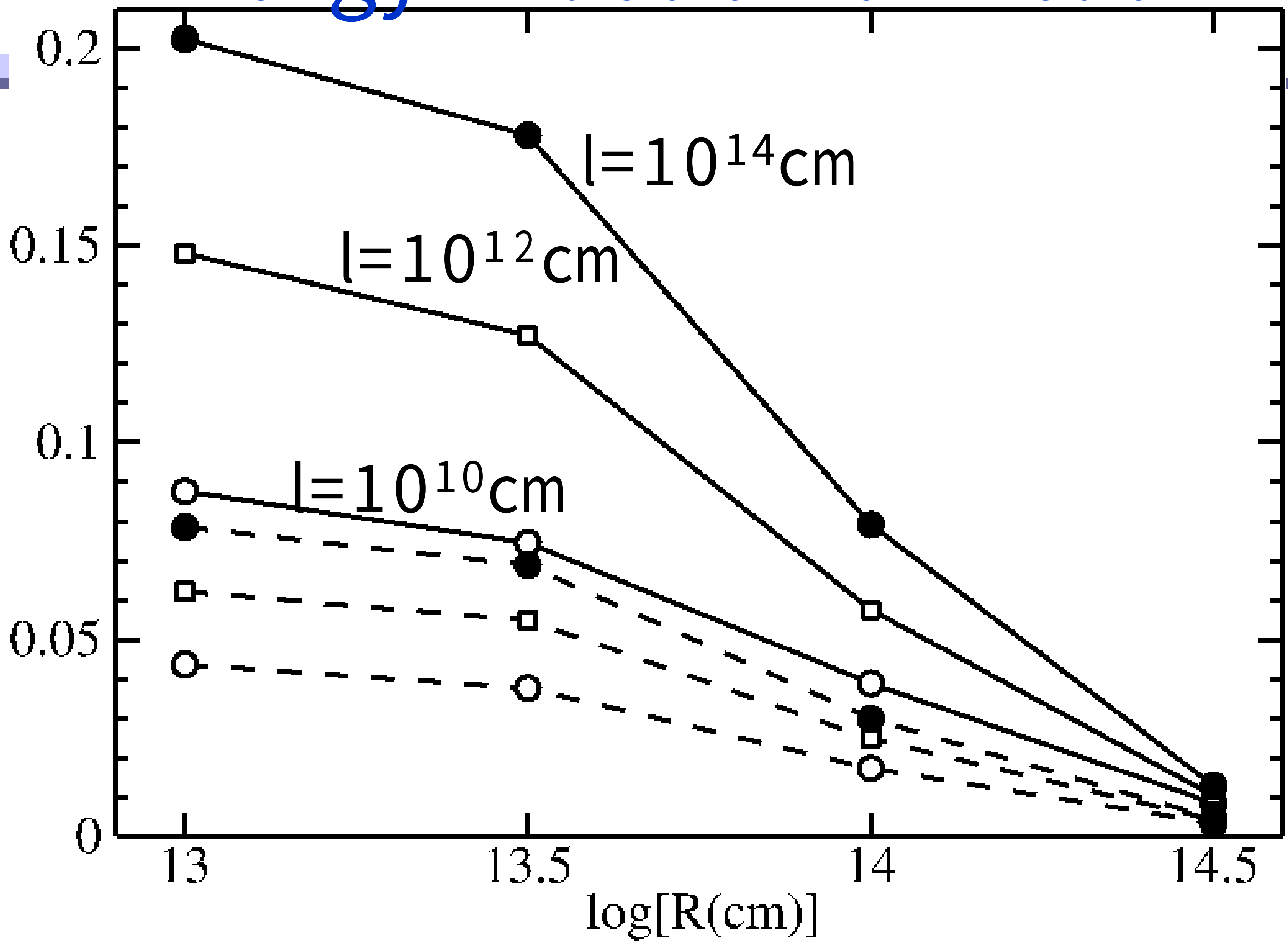
High Energy Cut-off

$\propto l^{0.5} R$

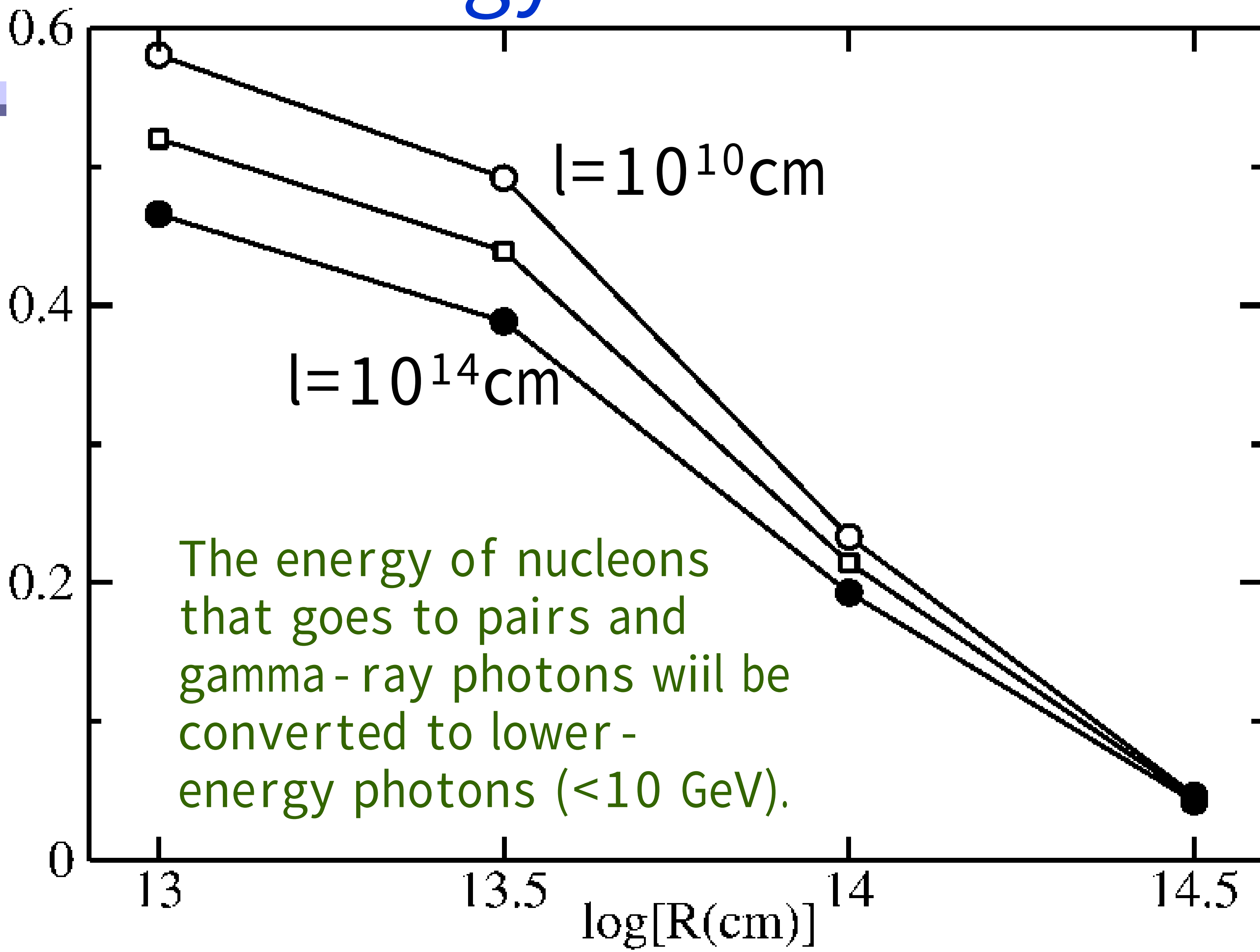
Low Energy Cut-off

$\propto R$

Energy Fraction of Neutrinos



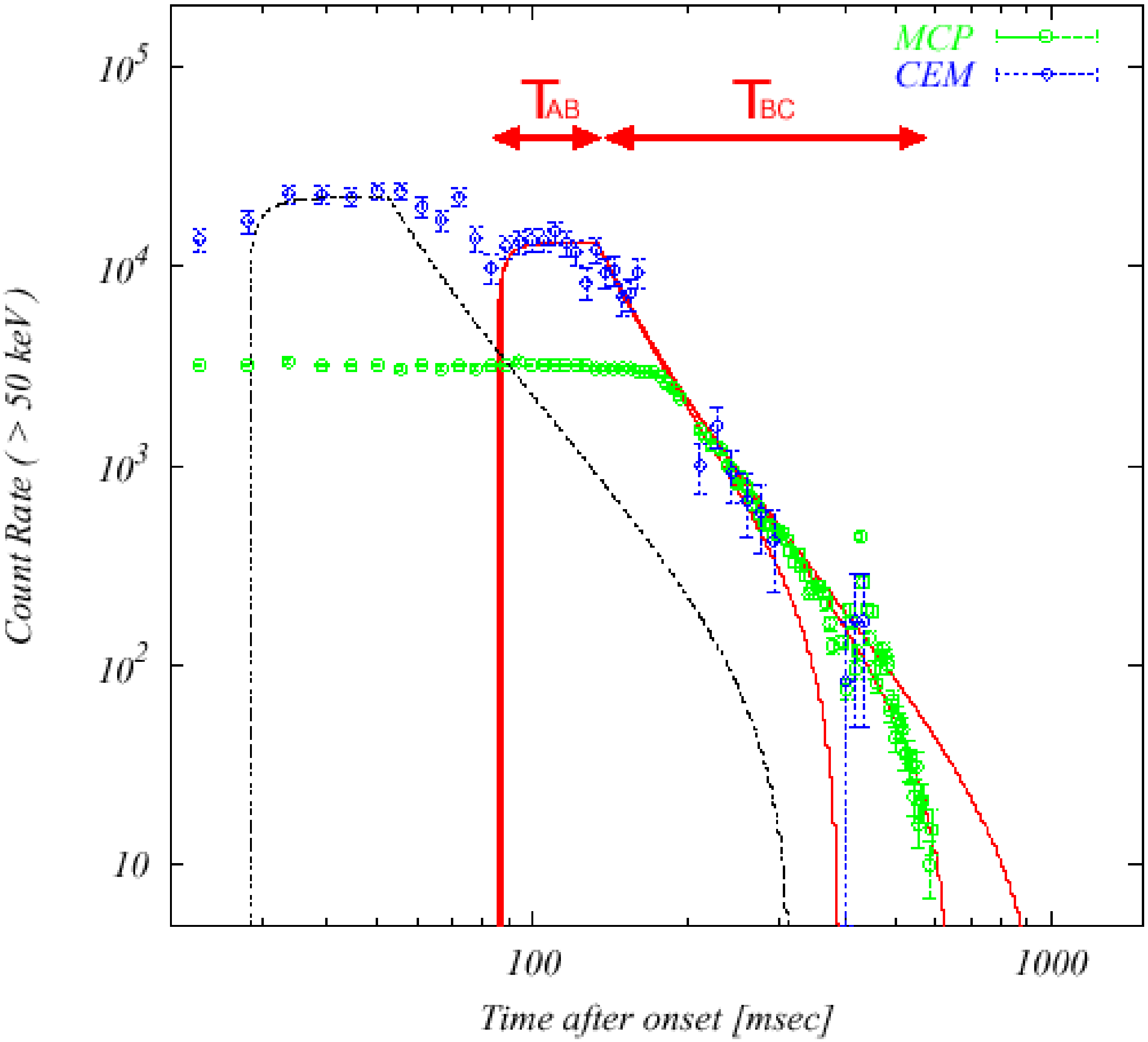
``Rest Energy" Nucleons lost



Conclusions

- In order to generate UHECRs bursts should occur at radii $>10^{14}$cm, though many pulses have < 1sec time scale.
- The parameters are strictly limited to produce both UHECRs and neutrino bursts at the same time.
- Neutrino spectra give us information on the physical condition of GRBs.
- Photons originated from pion cascade may contribute to GRB photons greatly.

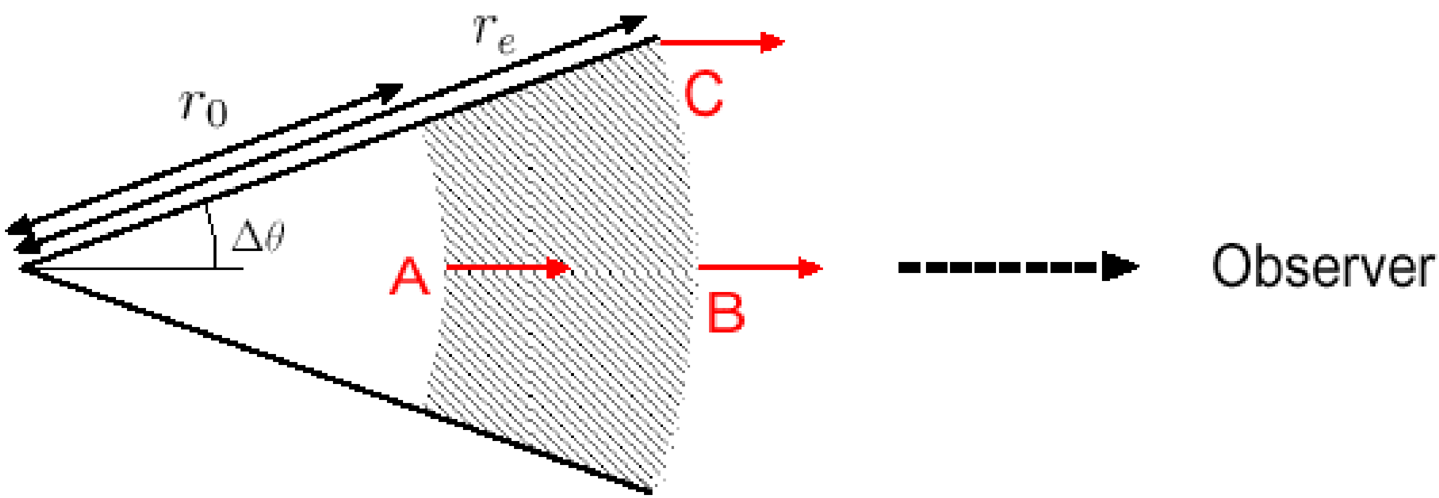
Comments on the Giant Flare from SGR 1806-20



GEOTAIL light curve is fitted by a jetted internal shock model (Yamazaki et al. 2005)

$$E_\gamma \approx 10^{46} \text{ erg}$$

Jet Model for SGR 1806-20



A thin shell moving with Lorentz factor γ starts to emit photons at r_0, and ends at r_e.

$$r_0 = 2.6 \times 10^8 \gamma^2 \ \text{cm}$$

$$r_e = 12.5 r_0$$

$$\Delta\theta = 3.1/\gamma$$

Another Model

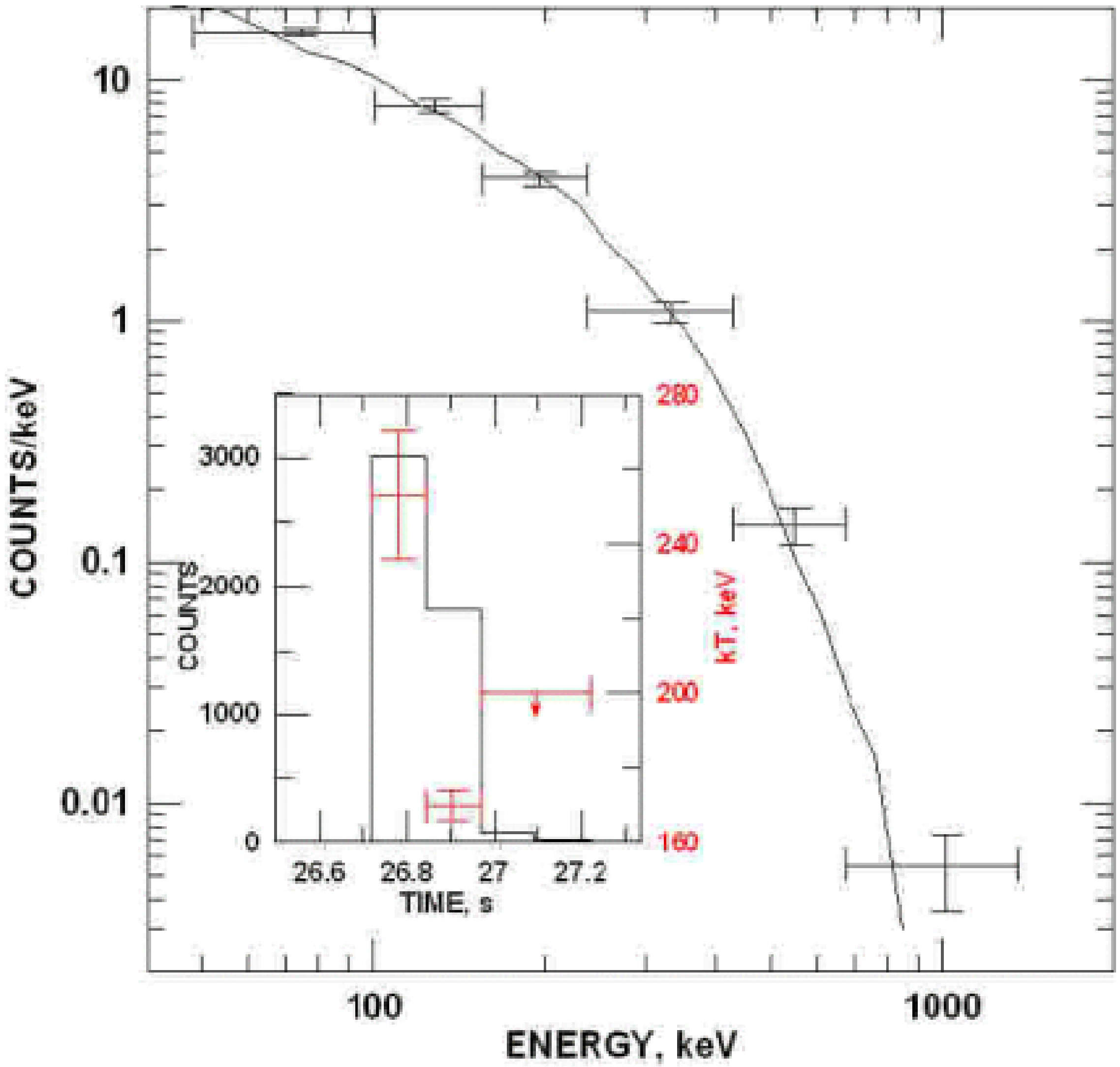
Pure radiation-pair fireball model

The fireball with $T \sim 200 keV$ expands.
The temperature decreases as $T \propto 1/R$.
At $T = 20$ keV and $\gamma = 10$ photons decouple.

↓

Thermal Photon spectrum
No shock wave

Thermal?



Hurley et al. 2005

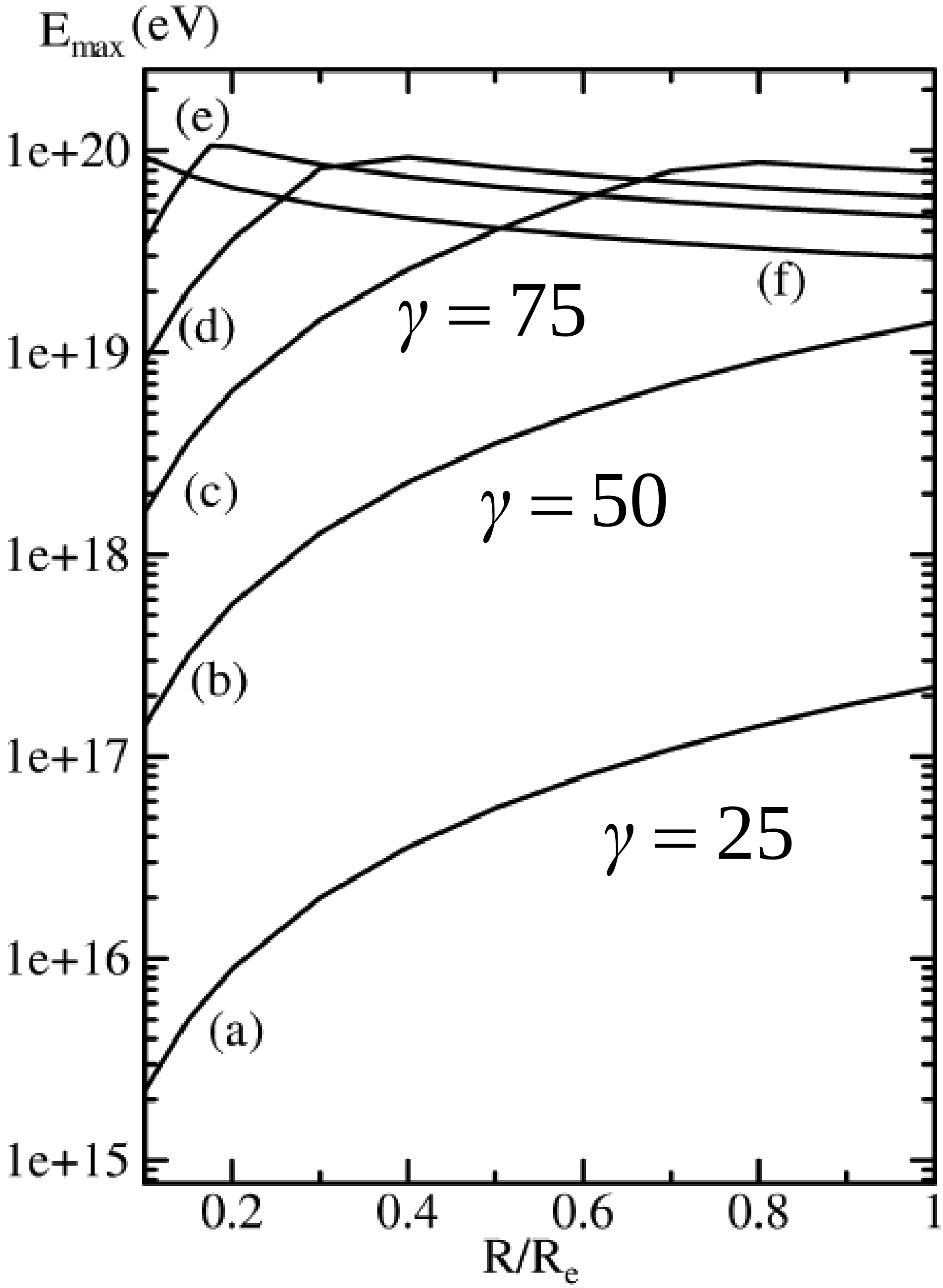
Which Model is Correct?

If the jet model is correct, the shocks may accelerate nucleons, and produce UHECRs.

UHECR detection is a key to determine the model.

Maximum Energy of UHECRs

1. The particle Larmor radius should be smaller than the size scale of the emitting region.
2. The cooling time due to synchrotron radiation should be longer than the dynamical time scale.



We calculate the maximum energy for the jet model for γ =25 - 200.

$\sim 10^{20}$eV

No Photopion Creation!

Since the giant flares are less luminous than GRBs, photopion production does not occur.

On the other hand, the magnetic fields and the scale of the emitting region are similar.

↓

UHECRs survive

AUGER observatory

The time delay between the flare and UHECRs is about 0.6 yr at least.
(largely depends on the structure of Galactic magnetic fields)

If the energy of UHECRS $>10^{20}$eV is 1% of photon energy, about 600 particles are detected by AUGER in a time scale 0.1 yr (or longer period).

Can SGRs be Primary Sources?

- 30 SGRs arouse the giant flare per 30yrs with total jet energy of 10^{46}erg.
- 0.1% of the jet energy goes to energy of UHECRs> 10^{19}eV.

↓

Enough to explain observed detection rate of UHECRs!

$\sim 10^{-9}$eV/cm^3

Conclusion

If UHECRs is detected, the jet model wins!
(if not, maybe...lose? low- γ ? long time delay?)

In addition it implies that flares from SGRs are main sources of UHECRs.