Multi-GeV lightcurves: possible hints for the emission mechanism

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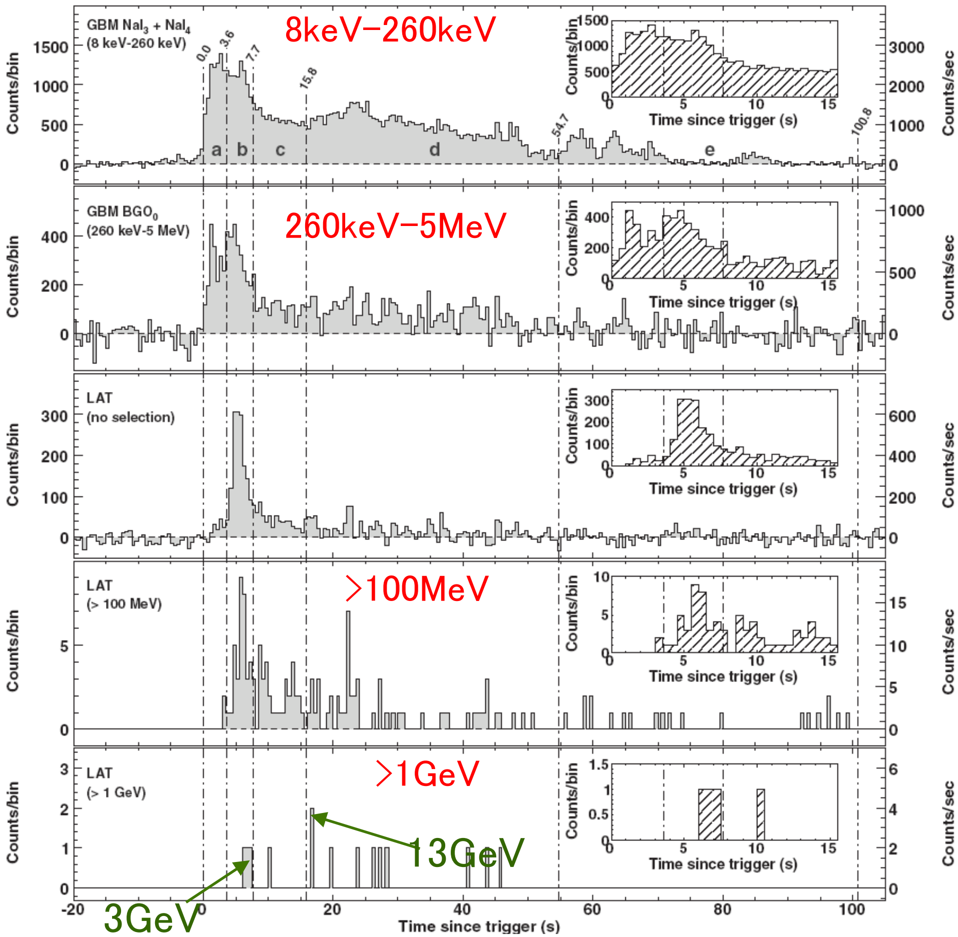
GeV photons from GRBs

GRB 080916C



Abdo+ 2009

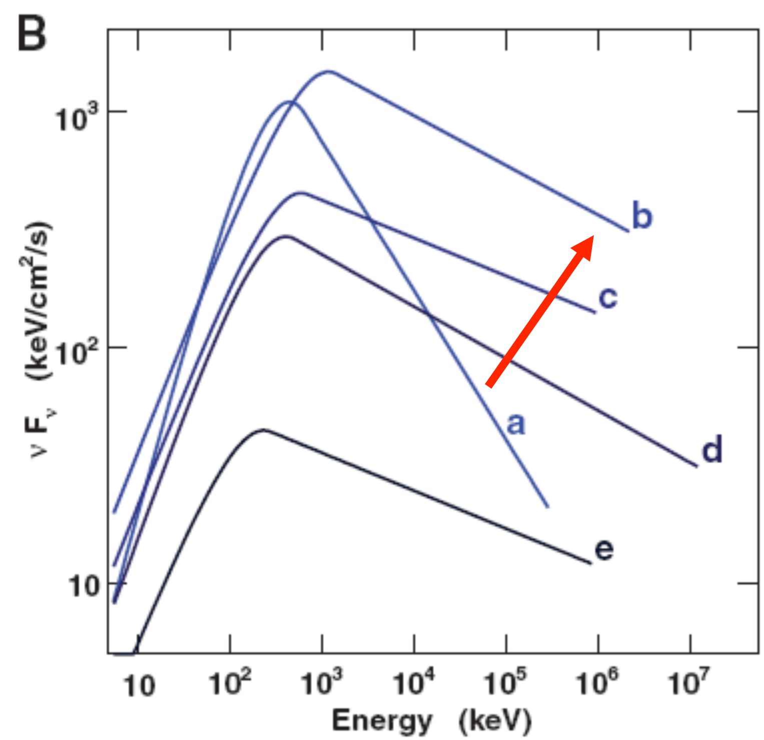
z=4.35

E_{iso}=8.8x10^{54}erg

Fermi detects GeV photons.

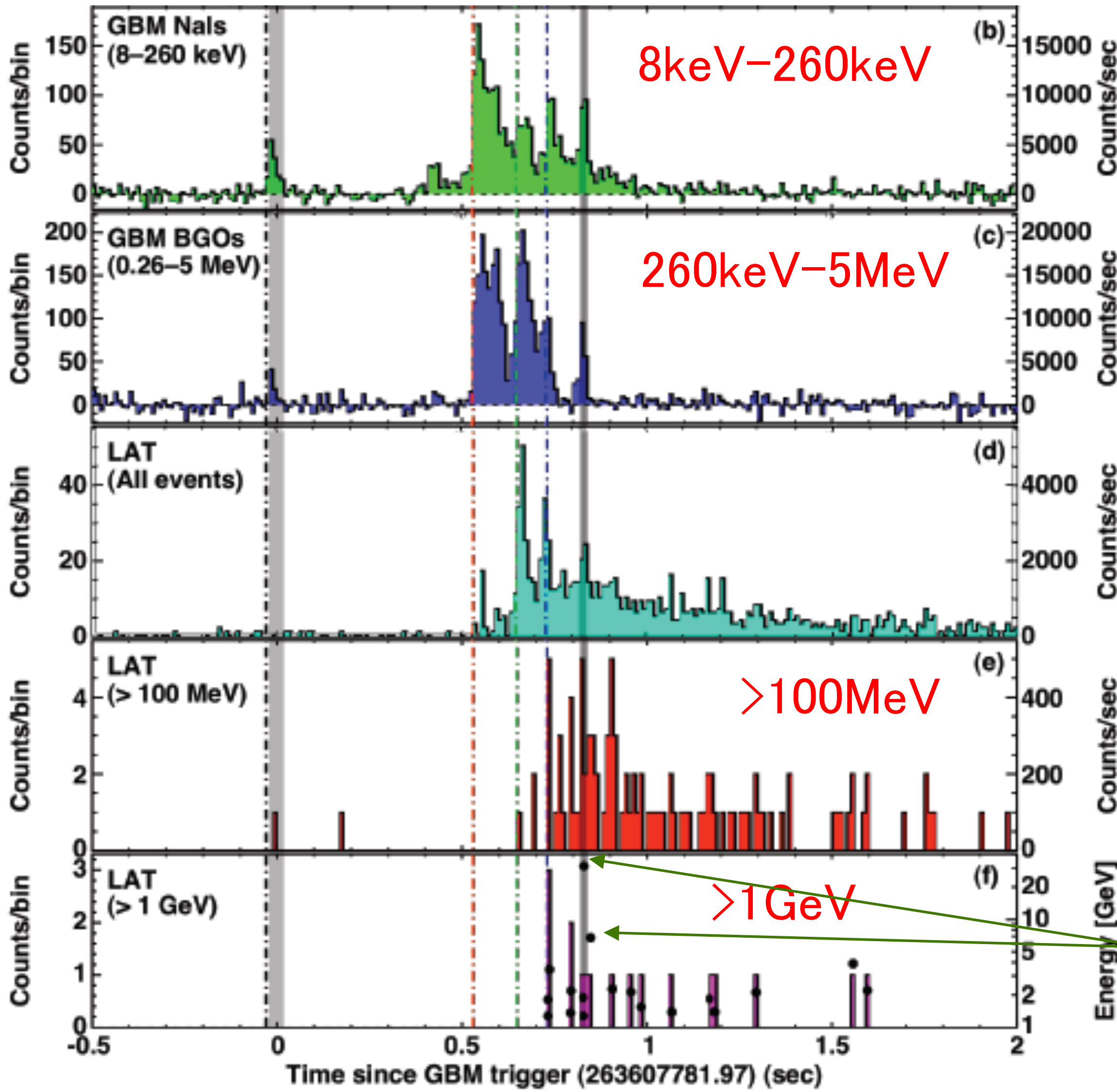
·Delayed onset

·Soft⇒Hard evolution



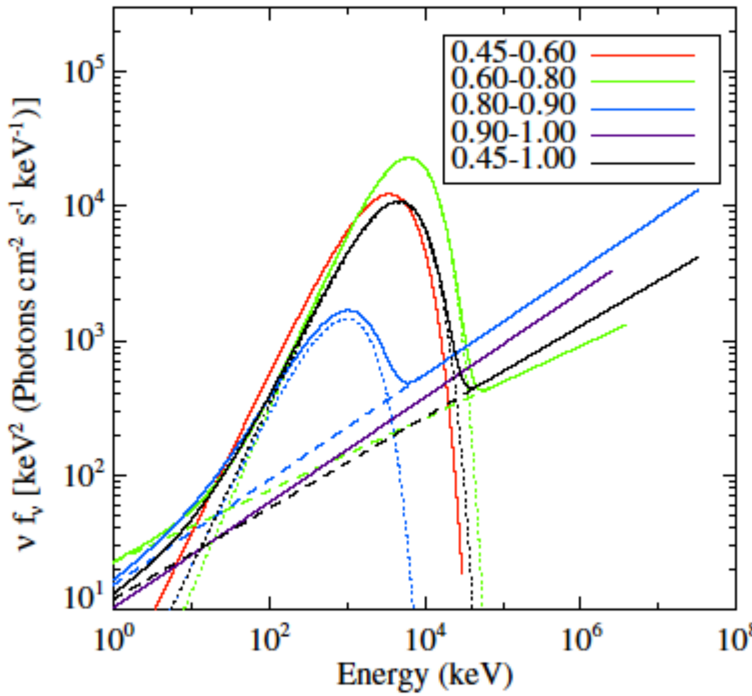
Band function(～broken power−law)

Extra component in GeV band



Abdo+ 2009

Short GRB 090510
delayed onset



Zhang+2011

31GeV, 3.4GeV

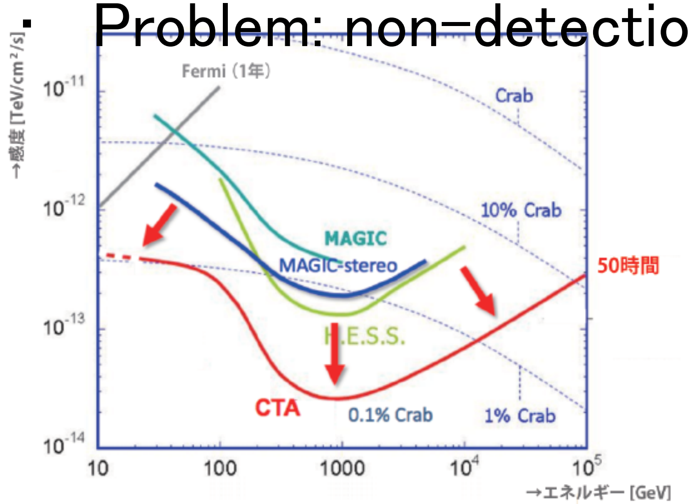
z=0.903

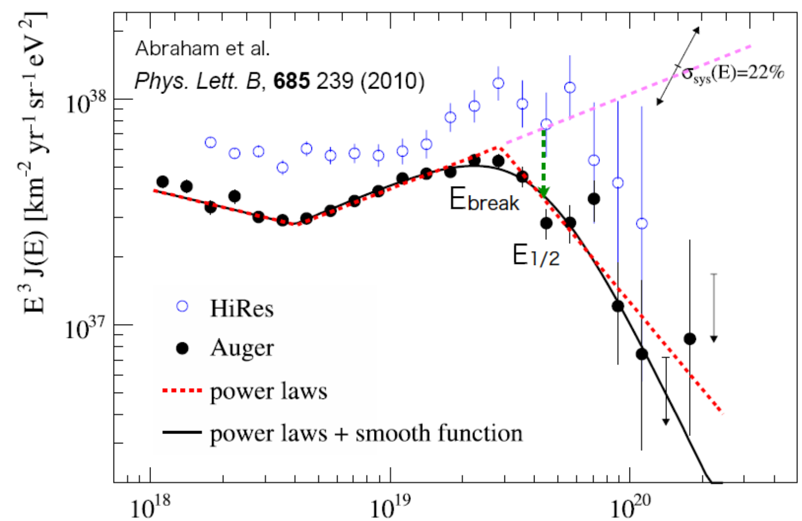
E_{iso}=10^{53}erg

Hadronic origin?

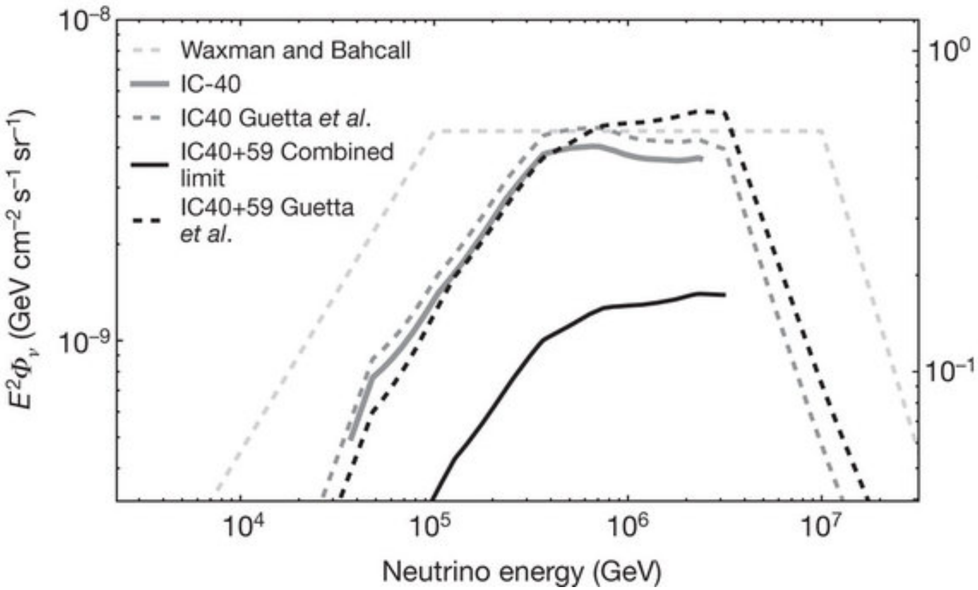
Bottcher & Dermer 1998; Gupta & Zhang 2007

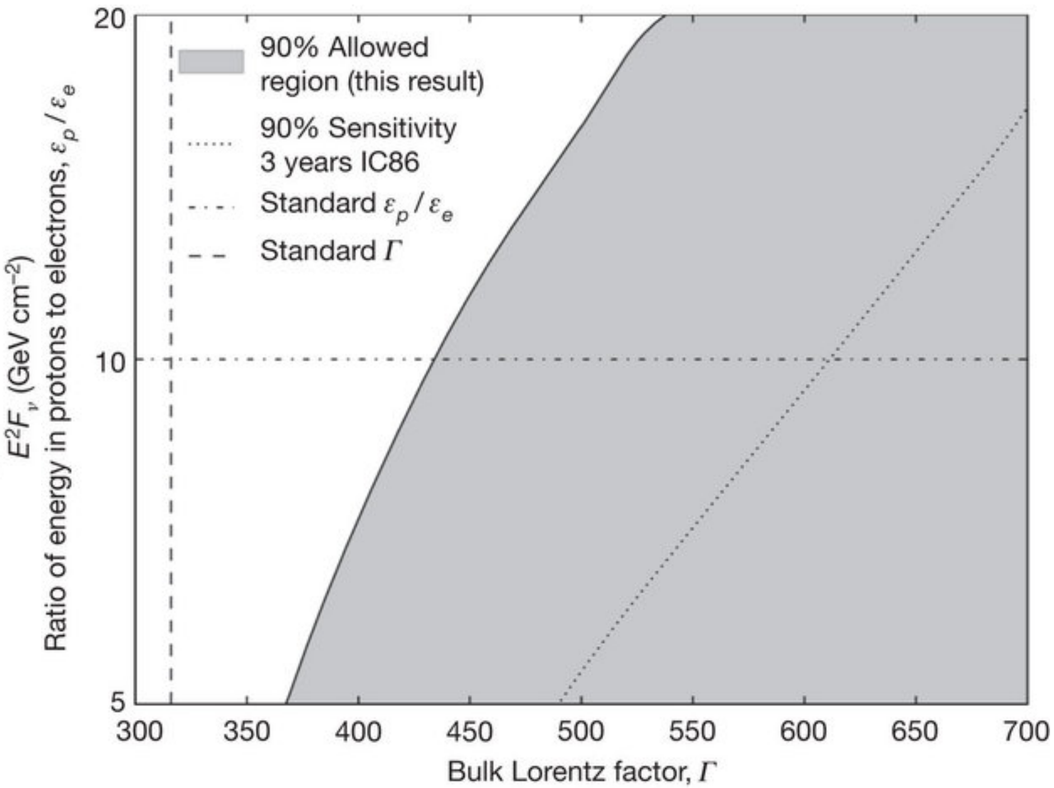
- GRB: promising candidate for UHECR sources (Waxman 1995, Vietri 1995).
- The delayed onset of GeV emission is due to the acceleration time of protons?
- Pion production is a slow process compared with lepton emission, which can also cause delayed GeV emissions.
- CTA may provide better photon statistics above 10 GeV (Gilmore + 12, Kakuwa+ 12)
- Problem: non-detection of Neutrinos?





Constraints by IceCube

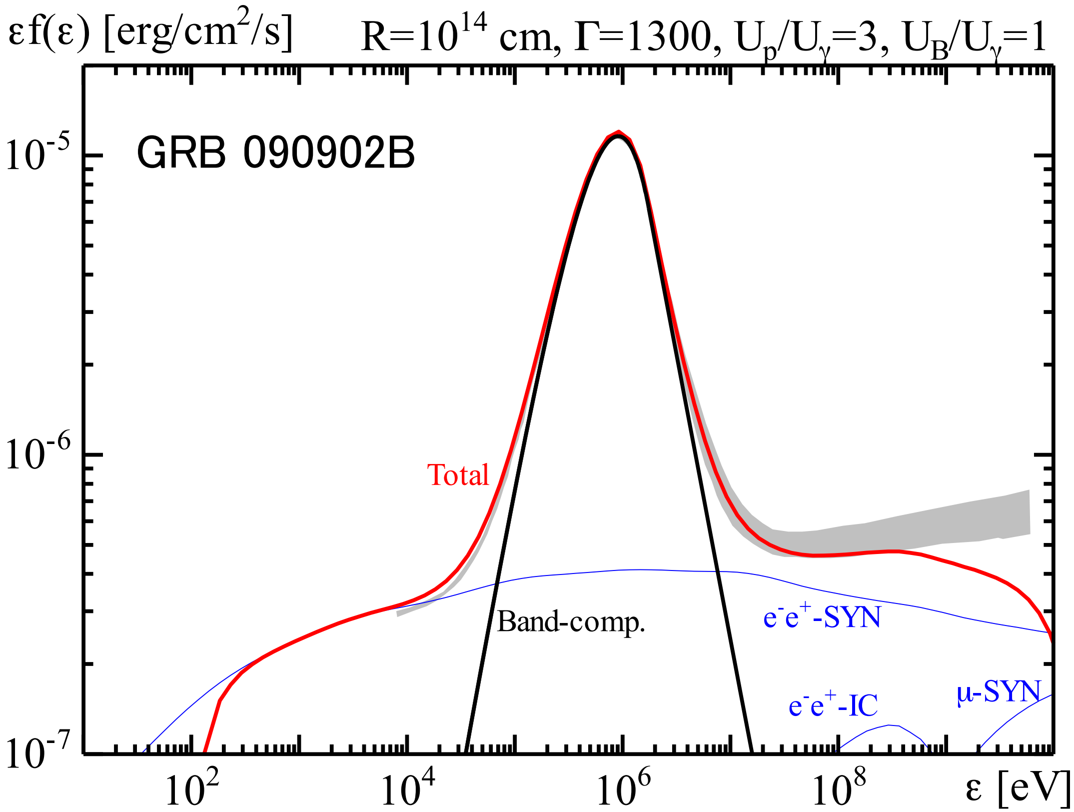




Abbasi+ 2012

High Lorentz factor is required to make GeV photons escape from the source.

Most favorable case for the hadronic model



Asano, Inoue and Meszaros 2010,

see also Asano, Guiriec & Meszaros 2009

- The MeV component is very narrow (photospheric?).
- The flat extra component would be due to synchrotron emission from pair cascade.
- We do not need IC, so the strong magnetic field is OK. As a result, the required amount of protons seems reasonable.
- The low-energy excess is also naturally explained.

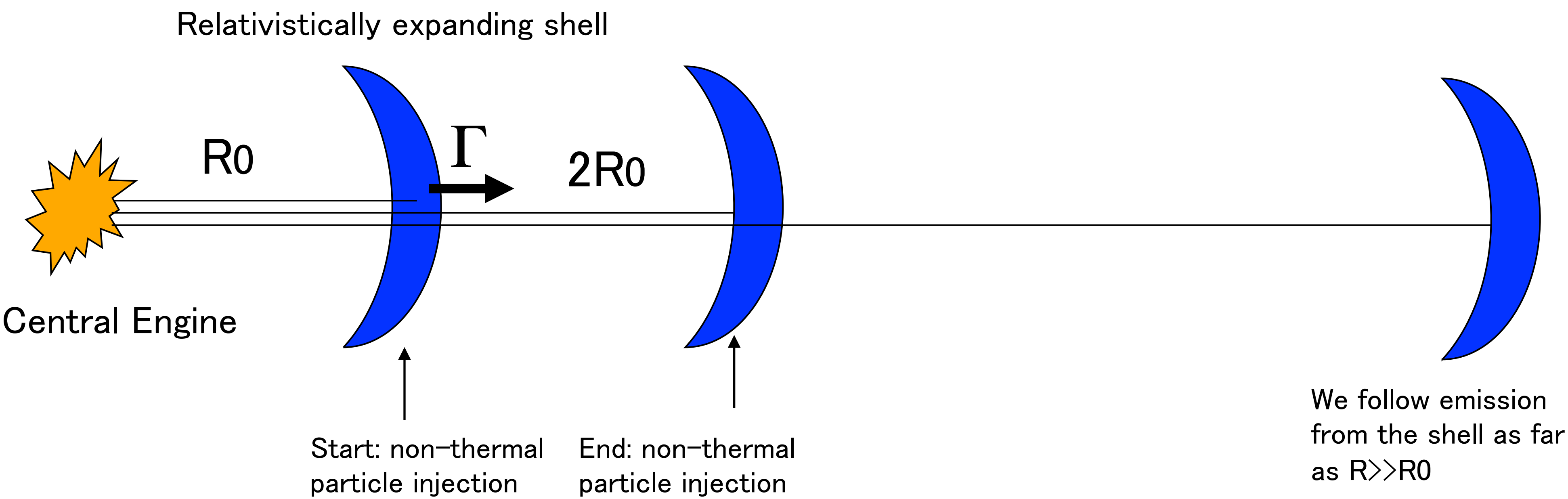
In the multi-GeV era with CTA etc., temporal evolution will be tested.

Time-dependent calculation

- The delayed onsets of GeV emission are hints for emission mechanism.
- We develop a time-dependent code:
  - Relativistically expanding shell (from $R=R_0$, $\Delta'=R_0/\Gamma$)
  - Electron injection during a finite time interval ($R<2R_0$)
  - Synchrotron
  - Inverse Compton (Thomson scat – Klein-Nishina regime)
  - Synchrotron self-absorption
  - Electron-positron pair creation
  - Adiabatic cooling
  - Photon escape
- Lagrangian scheme in energy space

See also Pe'er & Waxman 2005, Pe'er 2008, Belmont+ 2008, Vurm & Poutanen 2009, Bosnjak+ 2009, Daigne+ 2011

Time-dependent simulation



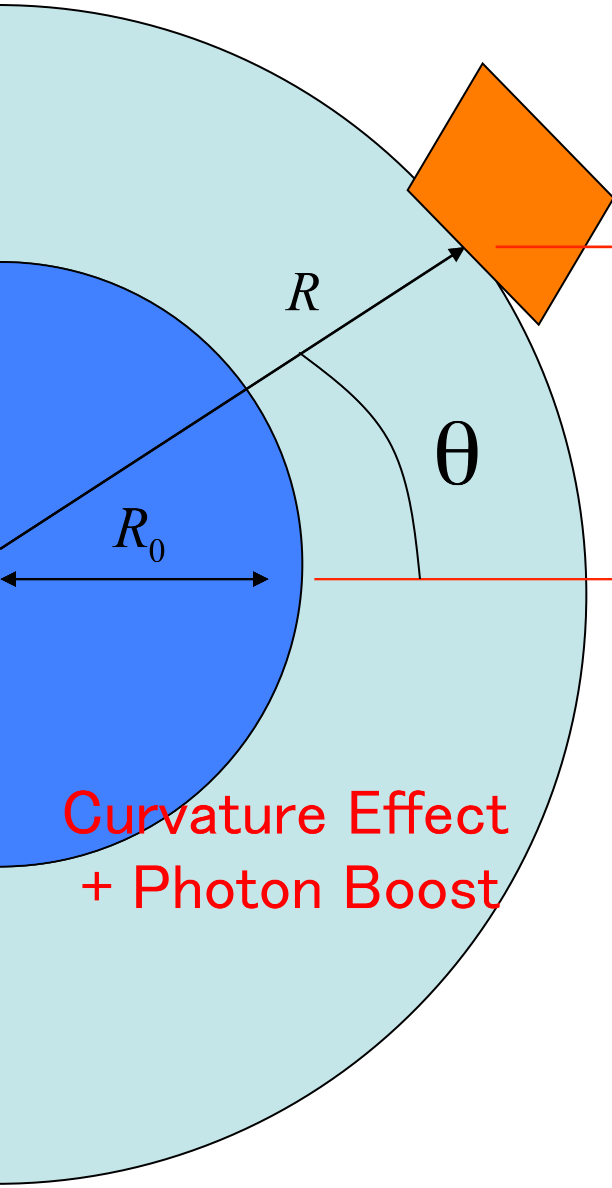
Inside the shell, we follow particle cooling via emission etc. with Lagrange-scheme in energy space.

Proton acceleration timescale

$$t_{\mathrm{acc}} = \xi \varepsilon_p / ceB$$

- $p(n) + \gamma \rightarrow p(n) + \pi^0 (\pi^+)$
- $p(n) + p \rightarrow p(n) + p + \pi^0 (\pi^+)$
- $p + \gamma \rightarrow p + e^+ + e^-$
- $\pi^0 \rightarrow \gamma + \gamma$, $\pi^+ \rightarrow \mu^+ + \nu_\mu$
- $\mu^+ \rightarrow e^+ + \nu_\mu + \nu_e$
- Synchrotron from p, π^+, μ^+
- Inverse Compton from p, π^+, μ^+

Lightcurve for observers



$$\frac{dN'}{d\Omega' dS'} = |\cos\theta'| \frac{n(\varepsilon')d\varepsilon'}{4\pi} c\Delta t'$$

both from foreside and backside

$$\Rightarrow \frac{dN'}{d\Omega'} = \frac{dN'}{d\Omega' dS'} \Delta S'$$

$$\cos\theta' = \frac{\cos\theta - \beta}{1 - \beta\cos\theta}$$

$$dS' = dS = 2\pi R^2 \sin\theta d\theta,\ d\Omega' = \frac{d\Omega}{\Gamma^2(1-\beta_{\rm sh}\cos\theta)^2},\ dN' = dN.$$

$$t_{\rm obs} = (1+z)\left[(1-\beta\cos\theta)\Gamma t' + R_0(1-\cos\theta)/c\right]$$

$$\varepsilon_{\rm obs} = \frac{\varepsilon'}{\Gamma(1-\beta\cos\theta)(1+z)}$$

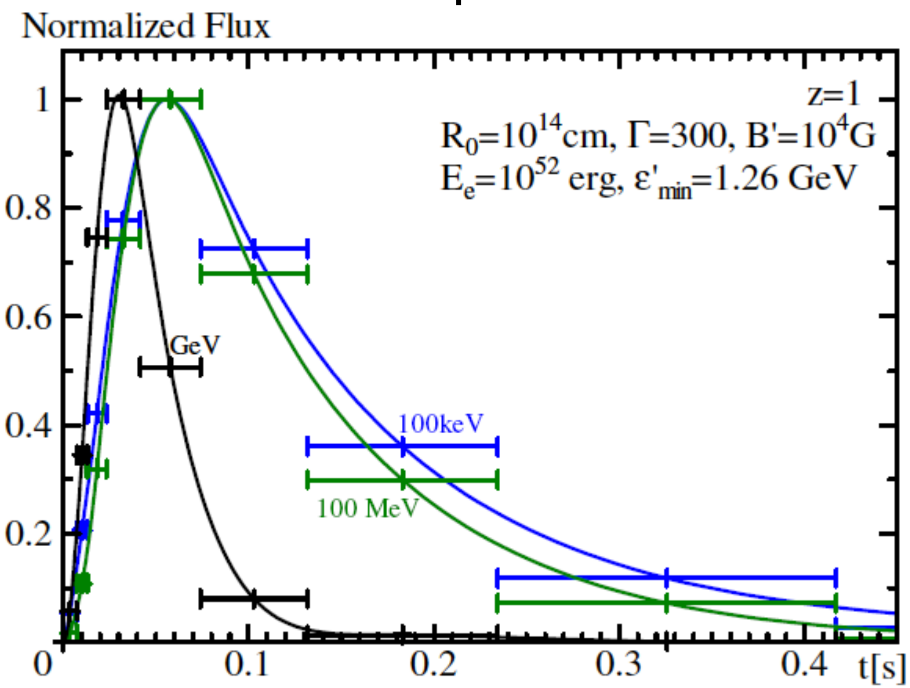
Fluence

$$N_{\rm obs} = \int d\Omega_{\rm obs} \frac{dN}{d\Omega},\ dS_{\rm obs} = D^2 d\Omega_{\rm obs}$$

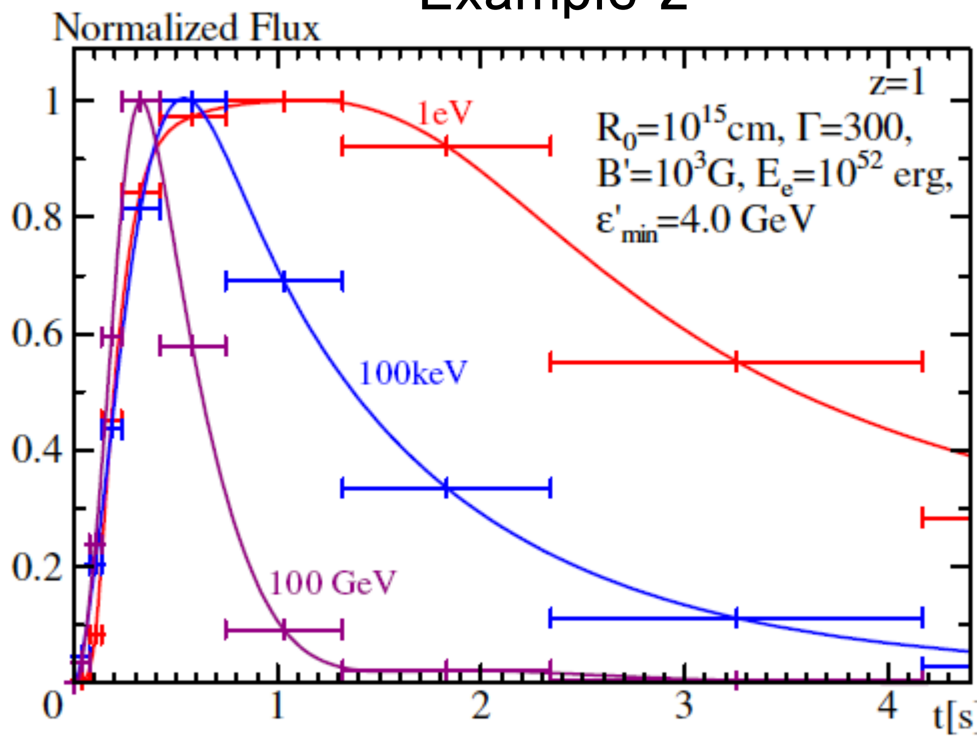
$$\Rightarrow \frac{dN}{dS_{\rm obs}} = \frac{1}{D^2}\frac{dN}{d\Omega},\quad D = D_{\rm L}/(1+z)$$

Spectral Evolution for leptonic models

Example 1



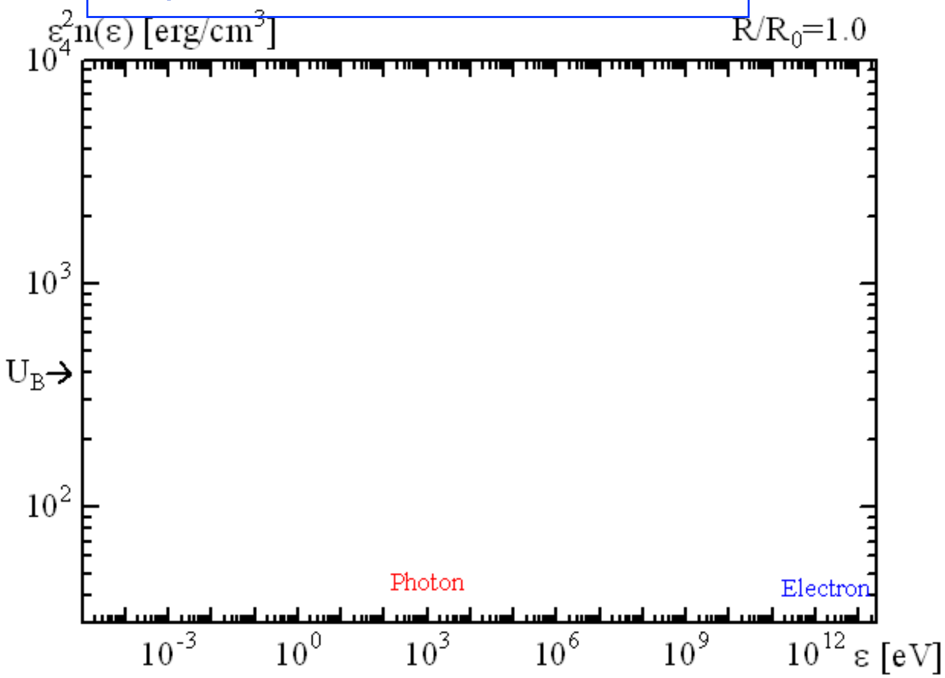
Example 2



When Gamma=300, the optical depth f¥grows with time. Then, GeV-TeV emissions ceases eariler. No-lag.

Leptonic–Extreme case, High Gamma and low B

Time-dependent simulation
Spectra in the shell frame



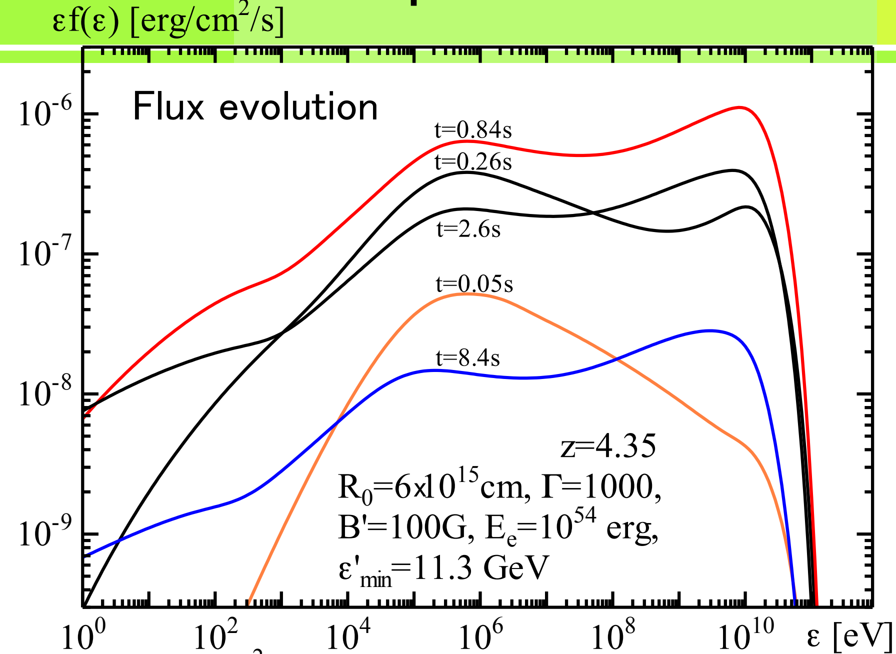
Asano & Meszaros 2011

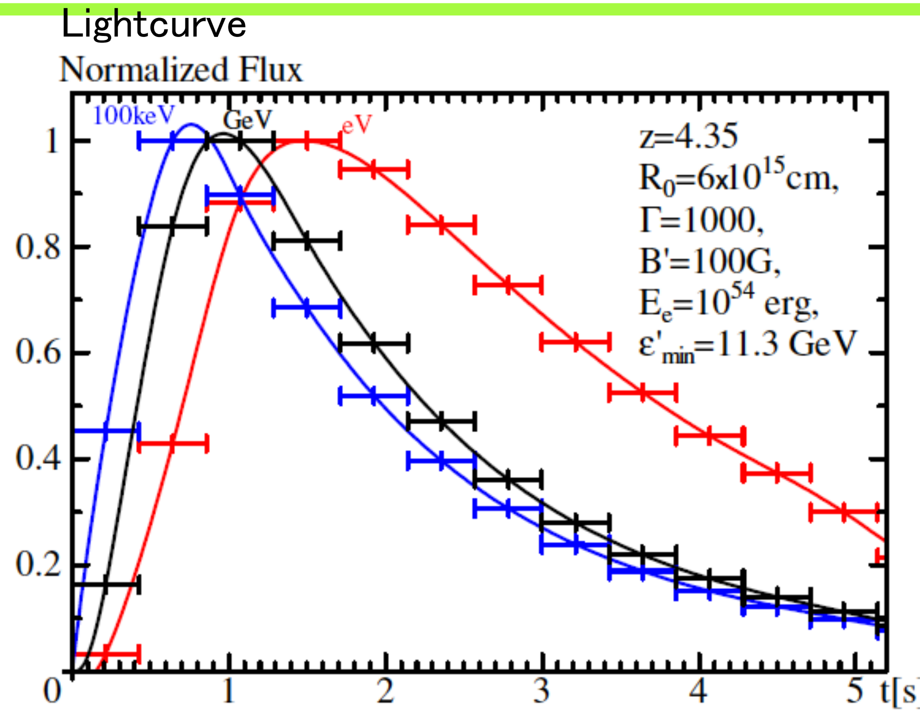
R_0=6x10^{15} cm, Γ=1000,
B'=100G, Ee=10^{54} erg,
γ'_{min}=11.3 GeV

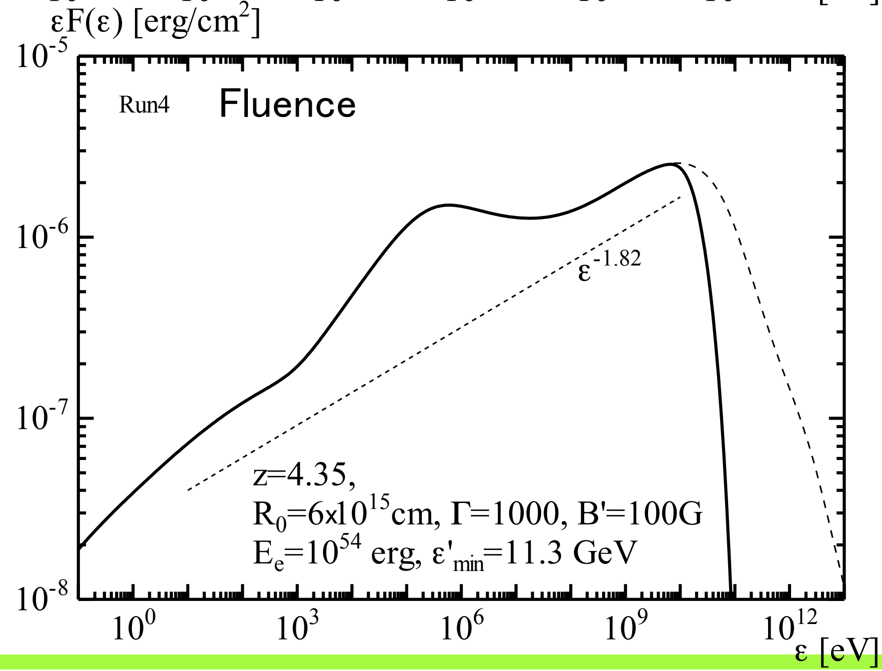
See also,
Pe'er & Waxman 2005
Vurm & Poutanen 2009
Bosnjak, Daigne, & Dubus 2009
Daigne, Bosnjak, & Dubus 2011

- Initially synchrotron component grows, and IC component grows later.
- In the later stage the injected electrons cool mainly via IC rather than synchrotron, so the synchrotron component starts to decay earlier than the IC component.
- After the end of the electron injection, the photon density decreases owing to the shell expansion and photon escape.
- At the end of the electron injection, cooled electrons are still relativistic so that "late synchrotron emission" continues and it produces a spectral bump at ∼0.1 eV.

Extreme-Leptonic case





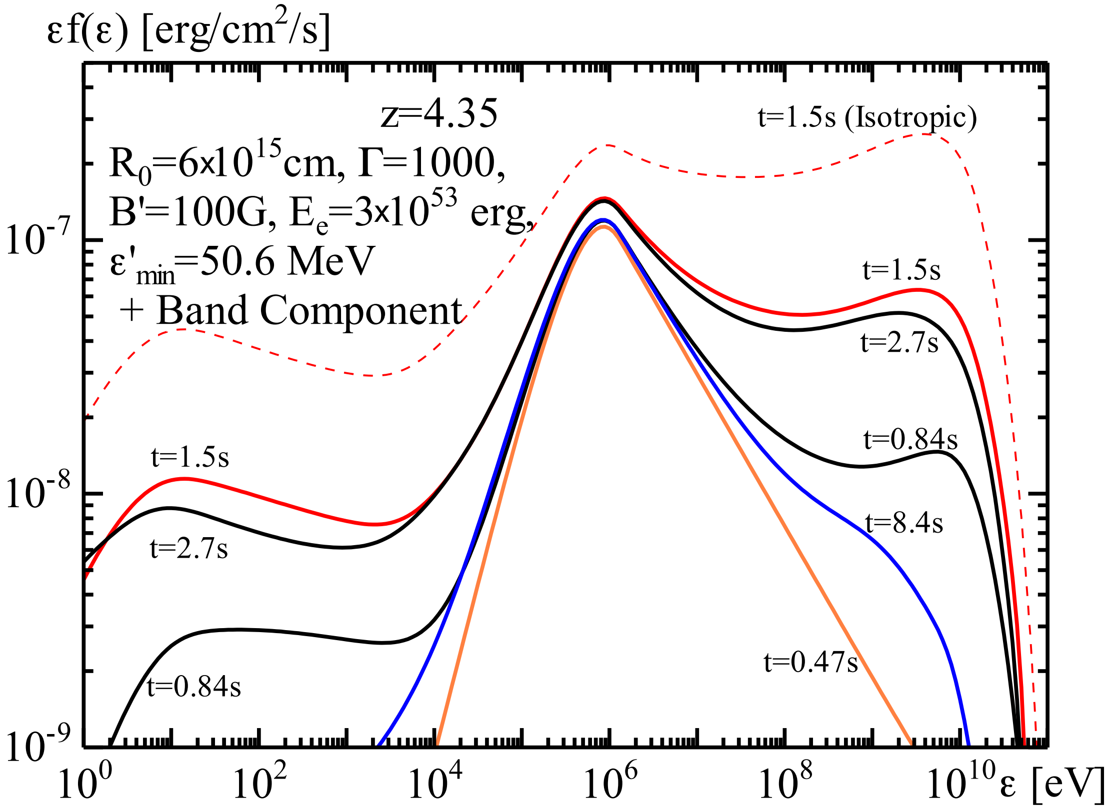


·IC and late synchrotron make a extra component.

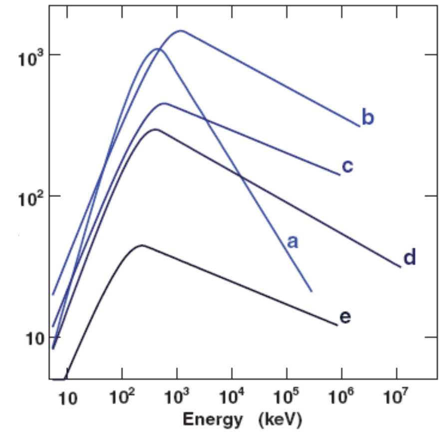
·Slow growth of the IC seed photons yields a delayed onset.

·FWHMs for MeV and GeV are almost the same.

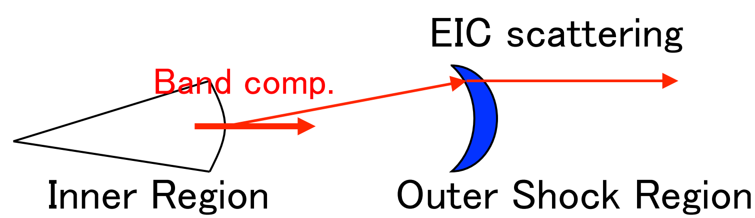
External photons + Internal shock



Thick: Fully-beamed approximation
Thin dashed: Isotropic approximation



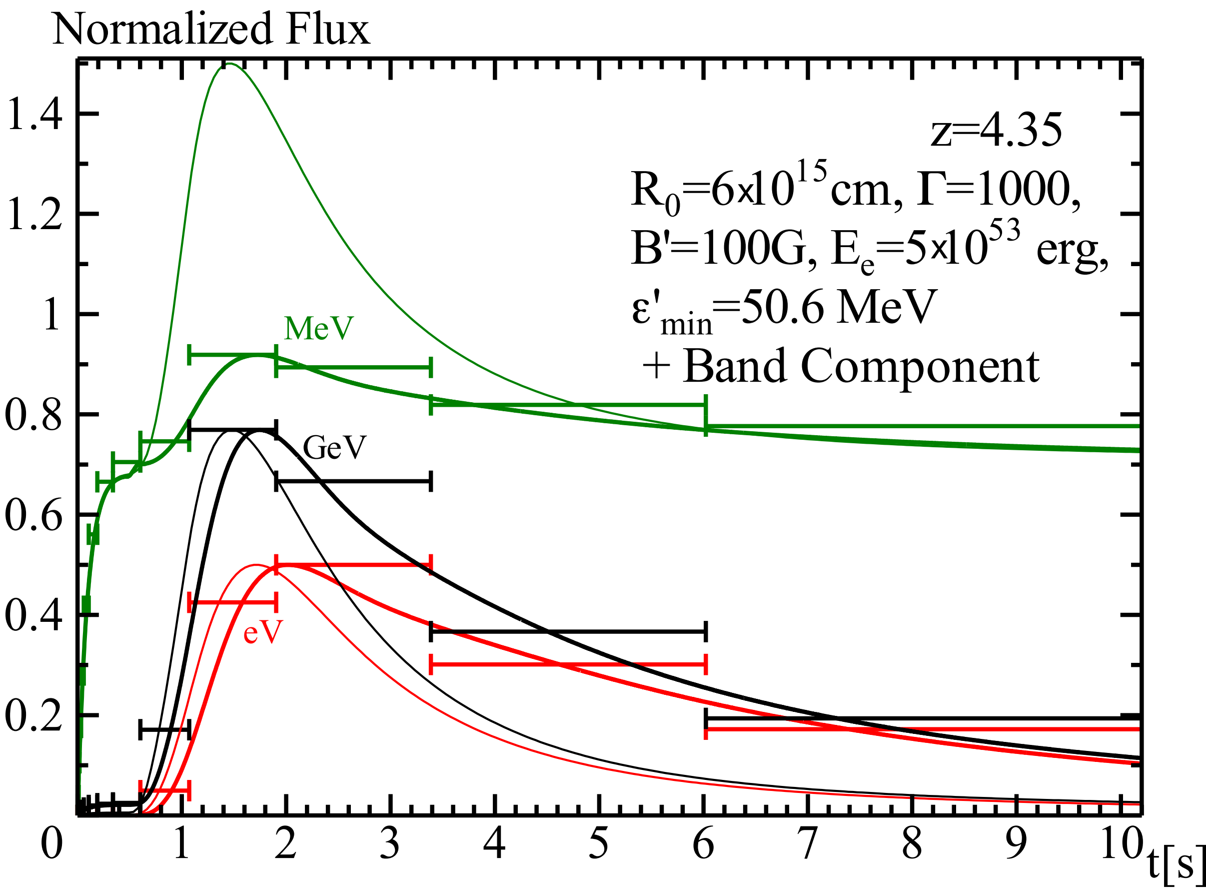
GRB 080916C
Abdo+ 2009



The seed photons coming from a inner region are anisotropic in the outer shell frame.
The anisotropy affects the flux evolution.

- Toma+ 2009, 2010
- External MeV component.
- GeV emission is due to up-scattering of MeV component.
- The spectral evolution is similar to the observation.

Lightcurves in leptonic-EIC model



Thick: Fully-beamed approximation

Thin dashed: Isotropic approximation

·The geometrical configuration in EIC model naturally yields the delayed onset of GeV emission.

·The anisotropy of seed photons in the shell frame leads to enhance emissions from higher latitude.

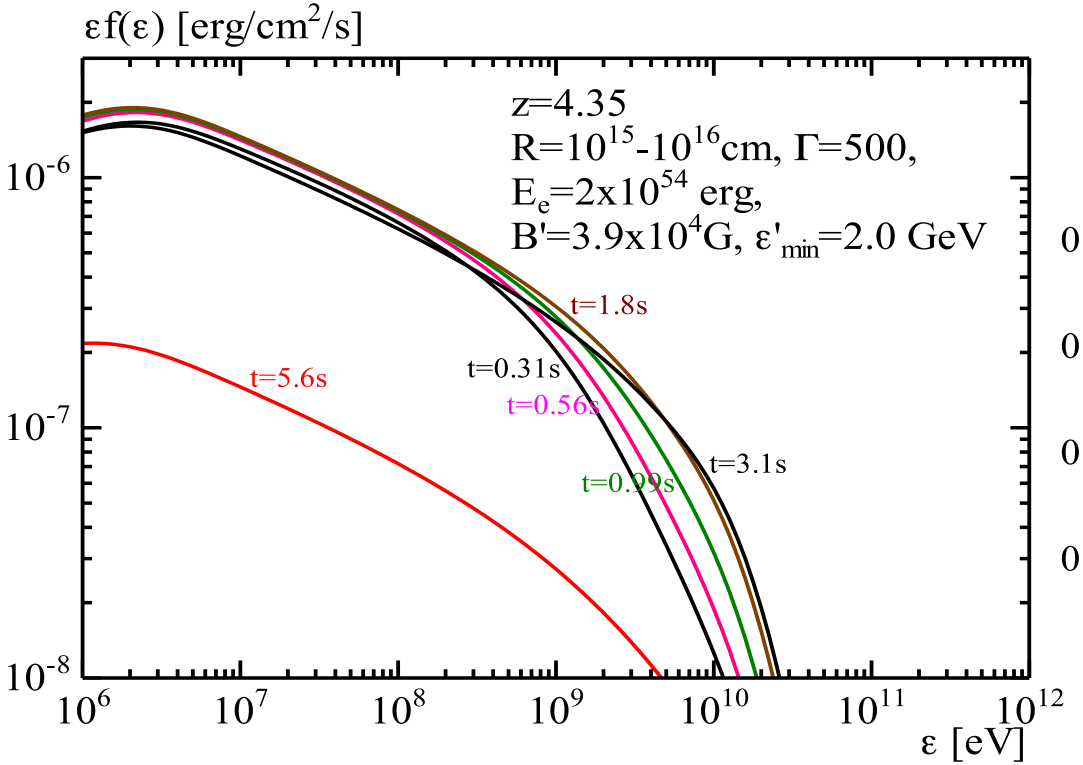
·The higher-latitude emissions lead to an extra factor for the delay timescale.

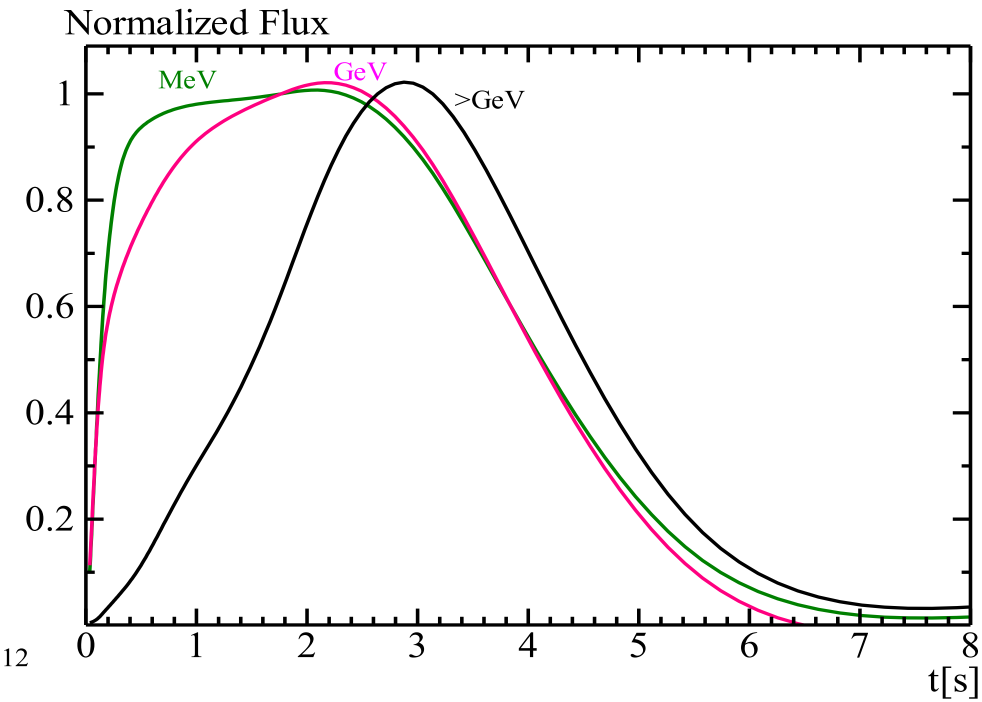
·The EIC model with anisotropic effect produces long tails of lightcurves.

Opacity decrease (leptonic)

Asano & Meszaros in prep.

Long particle injection during the shell expansion



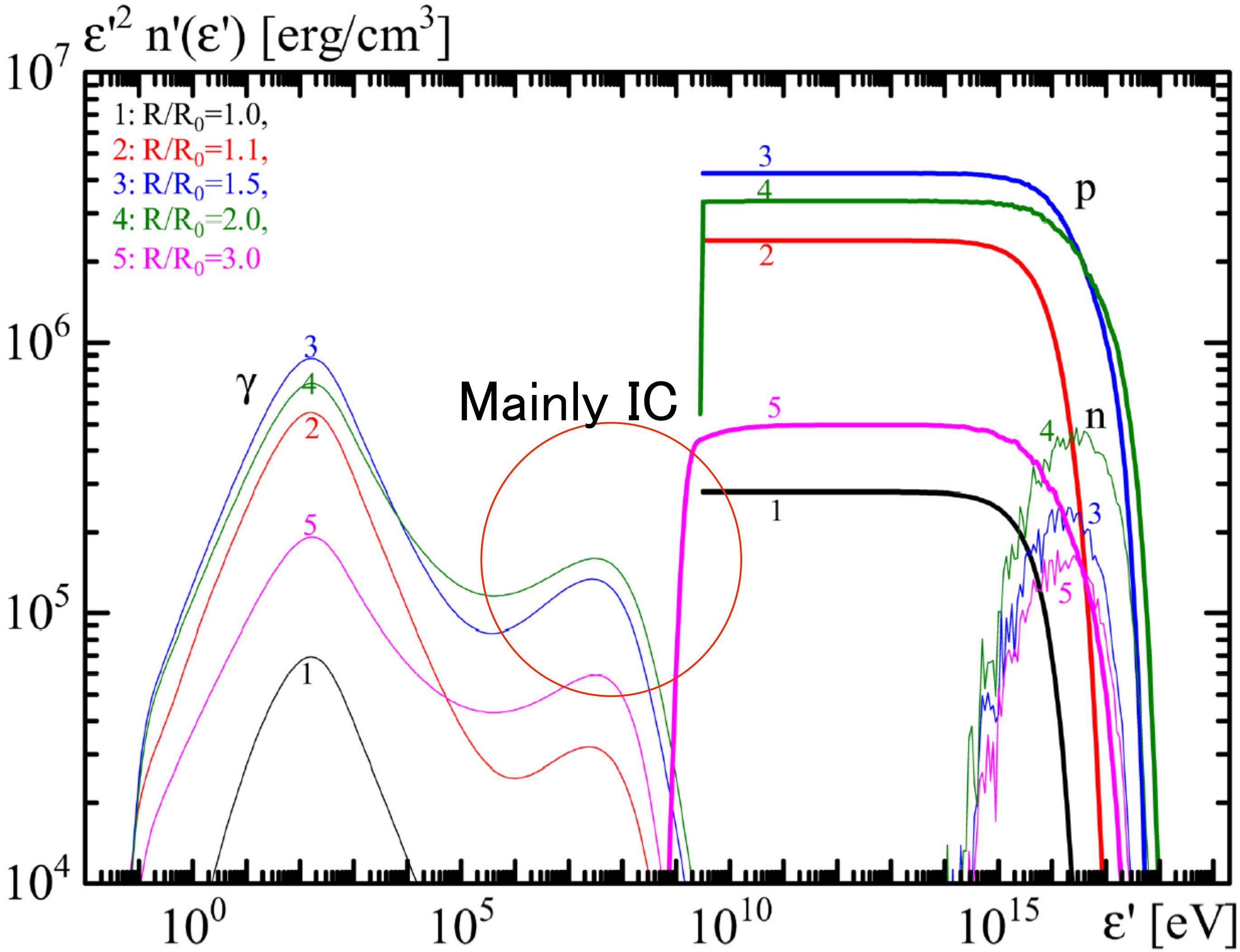


As the shell expands, the photon density decreases. Then, the gamma-gamma cut-off energy increases.

GeV: Lightcurve from the number-flux at GeV,
>GeV: Lightcurve from the integrated number-flux above GeV.

The spectral evolution is gradual, which is different from the observed sudden hardening.

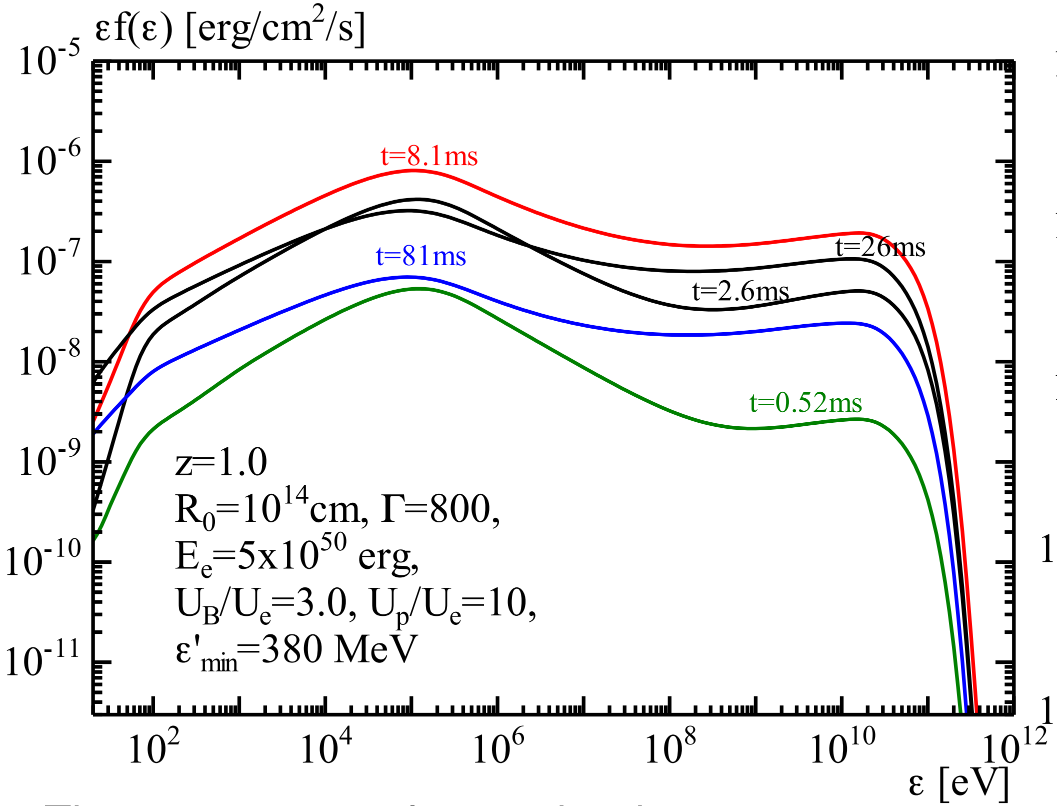
Hadronic model



- As protons are injected, the density increases, and the maximum energy grows with time.
- Even after the end of electron injection ($R>2R_0$), pion production continues. So the fraction of neutrons keep increasing.
- Adiabatic cooling for protons but neutrons.
- Leptonic IC photons contribute well in the high energy range.

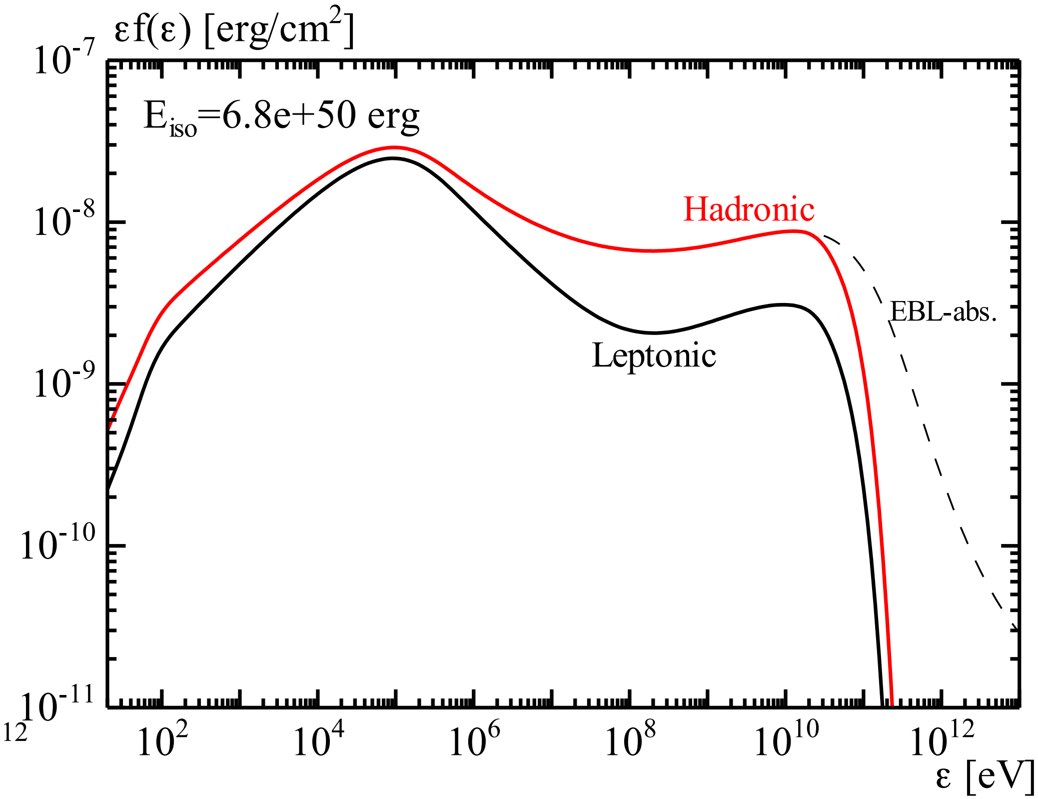
Spectra for the hadronic model

Flux evolution for an obsever



The spectrum evolves to hard one.

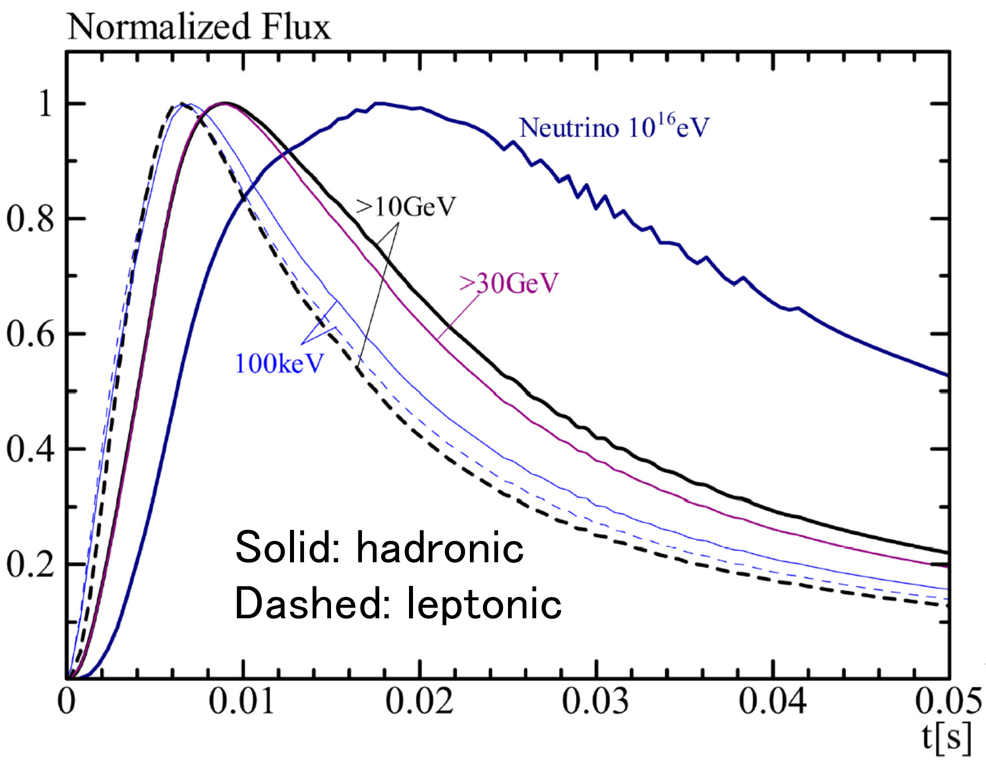
Fluence



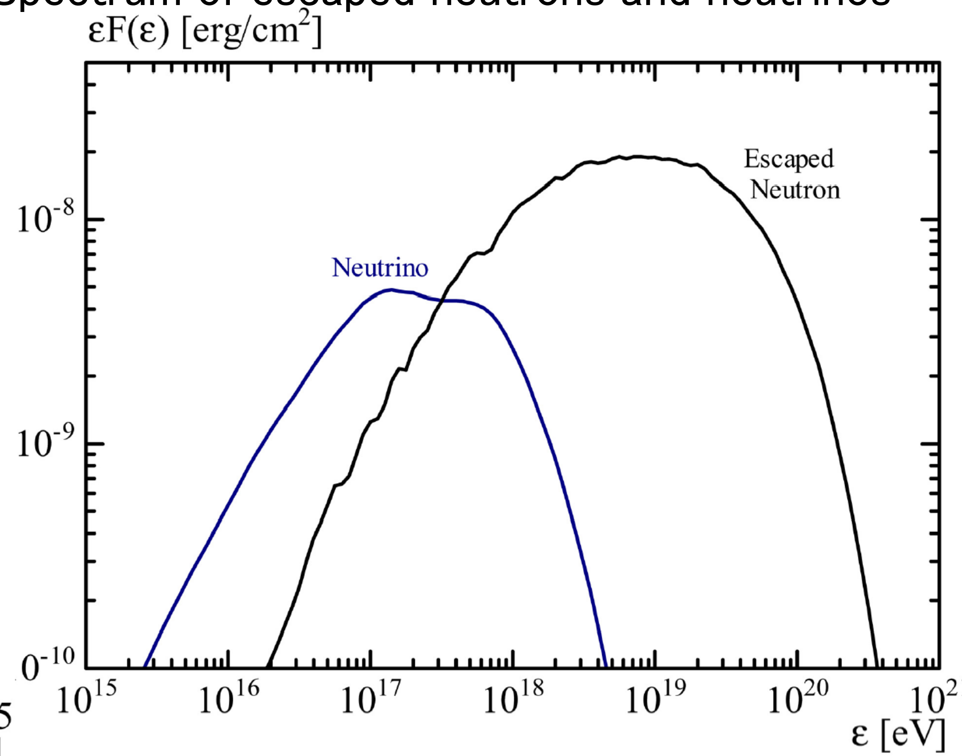
Both leptonic and hadronic models produce an extra component. It is hard to distinguish from only spectral shapes.

Hadronic model

Lightcurve



Spectrum of escaped neutrons and neutrinos



The GeV lightcurve shows broader one than the MeV curve, which is characteristic signature in the hadronic model.

IC photons contribute to GeV range, so the delay is shorter than that for neutrinos

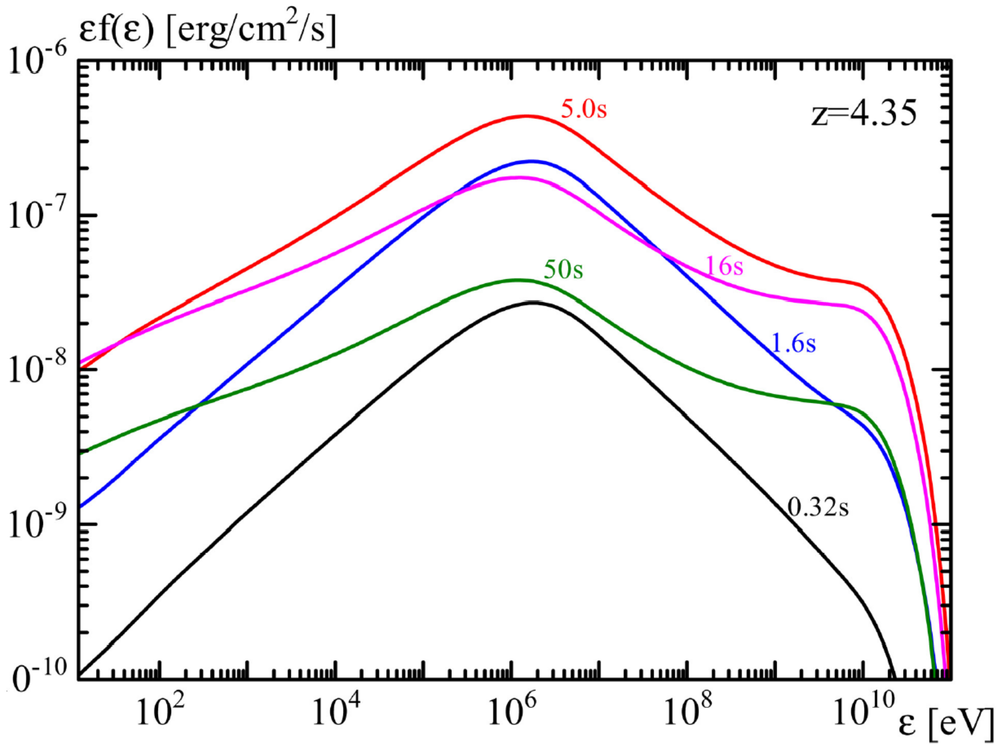
Here, we do not consider proton escape, which is pessimistic assumption for UHECR production.

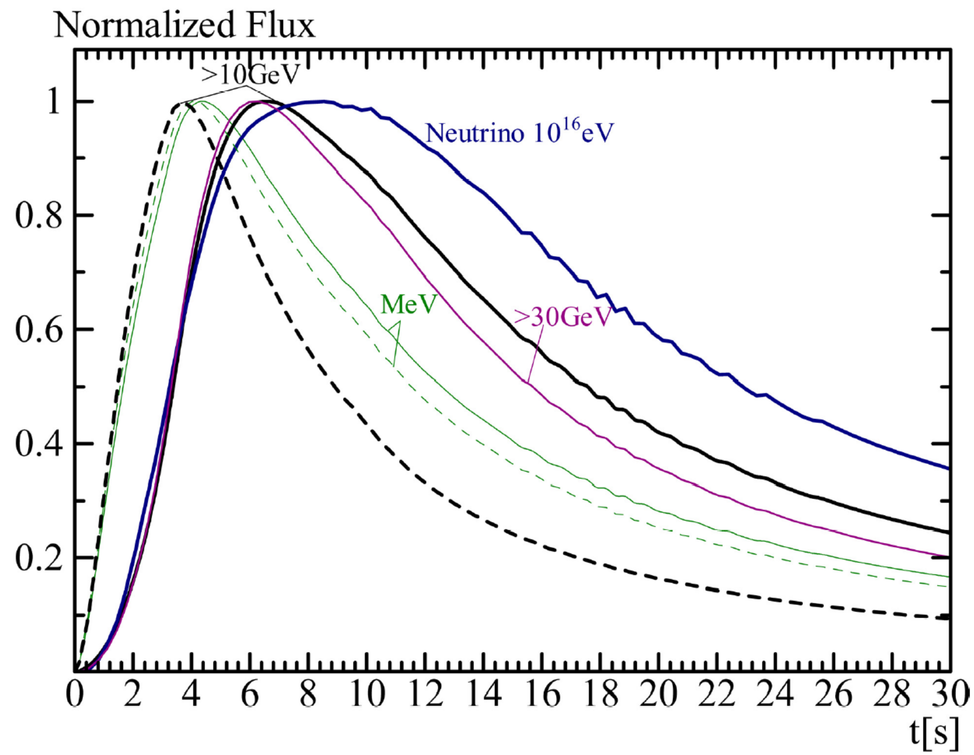
The energy of escaped UHE neutrons is comparable to gamma-ray energy.

The neutrino energy range is well above the IceCube limit.

Hadronic model with large R

$\Gamma = 600$, $R_0 = 1.3 \times 10^{16}$ cm, $E_{\rm e,iso} = 2.0 \times 10^{54}$ erg, and $E_{\rm p,iso} = 4.8 \times 10^{55}$ **erg** ($\epsilon_{\rm p}/\epsilon_{\rm e} \simeq 24$) **including the acceleration effect after injection.** The initial magnetic field $B'_0 = 830$ G is determined by the same method in §4.1 as $\epsilon_B/\epsilon_{\rm e} = 3.0$ at $R = 2R_0$. The peak energy $\varepsilon_{\rm peak}$ is adjusted to be ~ 1 MeV by adopting $\varepsilon'_{\rm e,min} = 13$ GeV.





The Klein–Nishina effect prevents leptonic–IC.
GeV photons are originated from mainly hadronic cascade.
So the GeV and neutrinos have the comparable delay timescales.

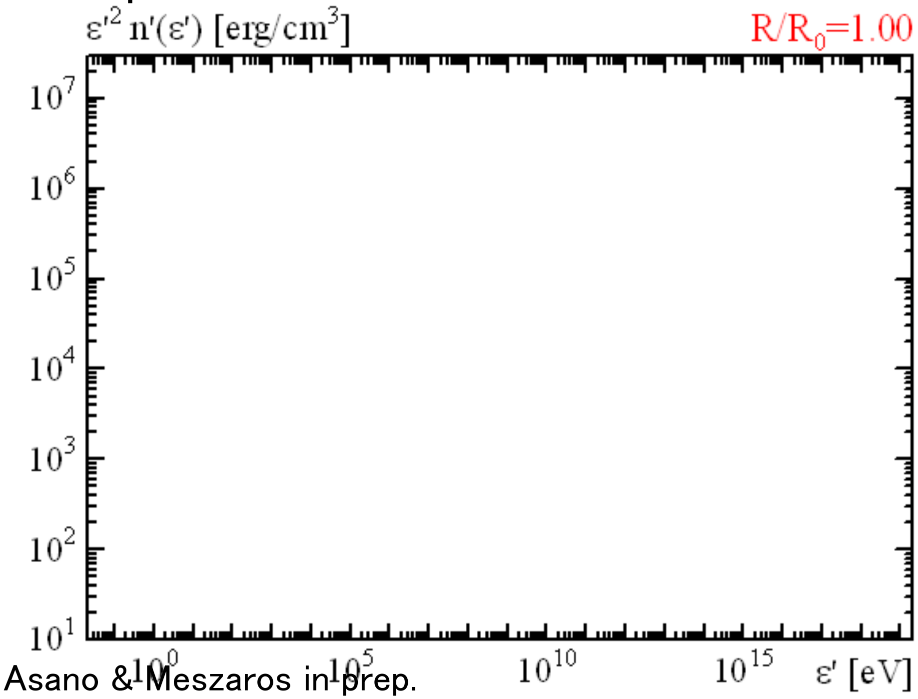
Summary

- Leptonic+Very weak magnetic field: the slow evolution of SSC due to the Klein–Nishina effect results in a delayed onset of the GeV emission.
- However, in such leptonic models the FWHM of the GeV lightcurve is almost the same as that of the 0.1–1MeV lightcurves
- External inverse Compton (EIC) model: GeV–delay + a long tail for the GeV lightcurve
- The pair creation–opacity evolution effect: the growth of the cutoff energy is more gradual than in the current sample of Fermi–LAT bursts.
- Hadronic: the wider FWHM for the GeV lightcurve than for then MeV lightcurve.
- If the Klein–Nishina effect prevents IC emissions, the delay due to hadronic cascade becomes more dominant.
- The amounts of escaped neutrons in our examples are within an acceptable range for acting as UHECR sources.
- Neutrino–delay is more prominent.
- CTA or other Cerenkov telescopes may provide much better photon statistics, which can be a hint to distinguish the models.

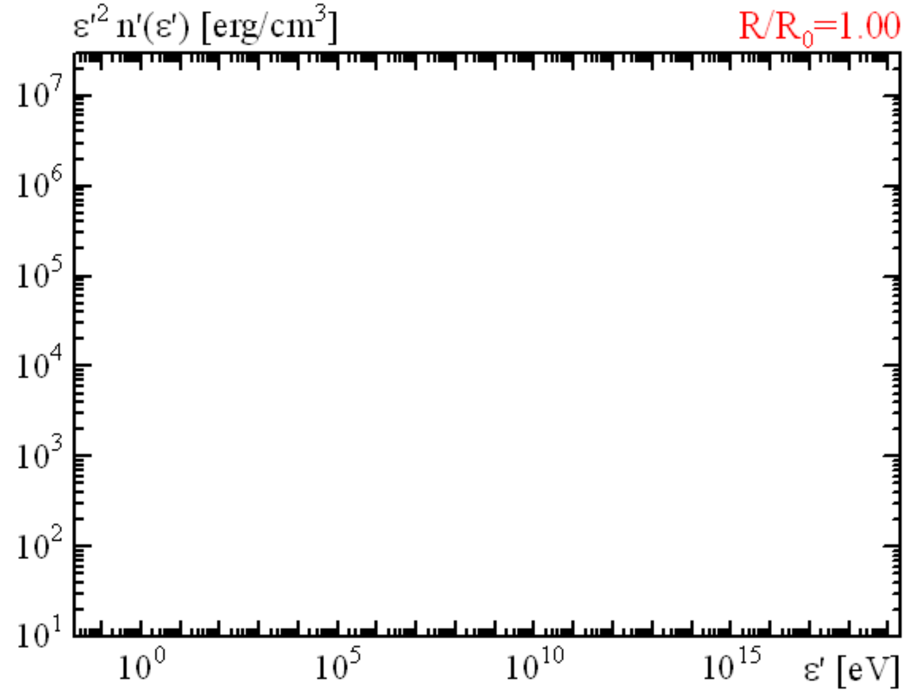
予備スライド

Particle distribution in the shell frame

Leptonic



Hadronic



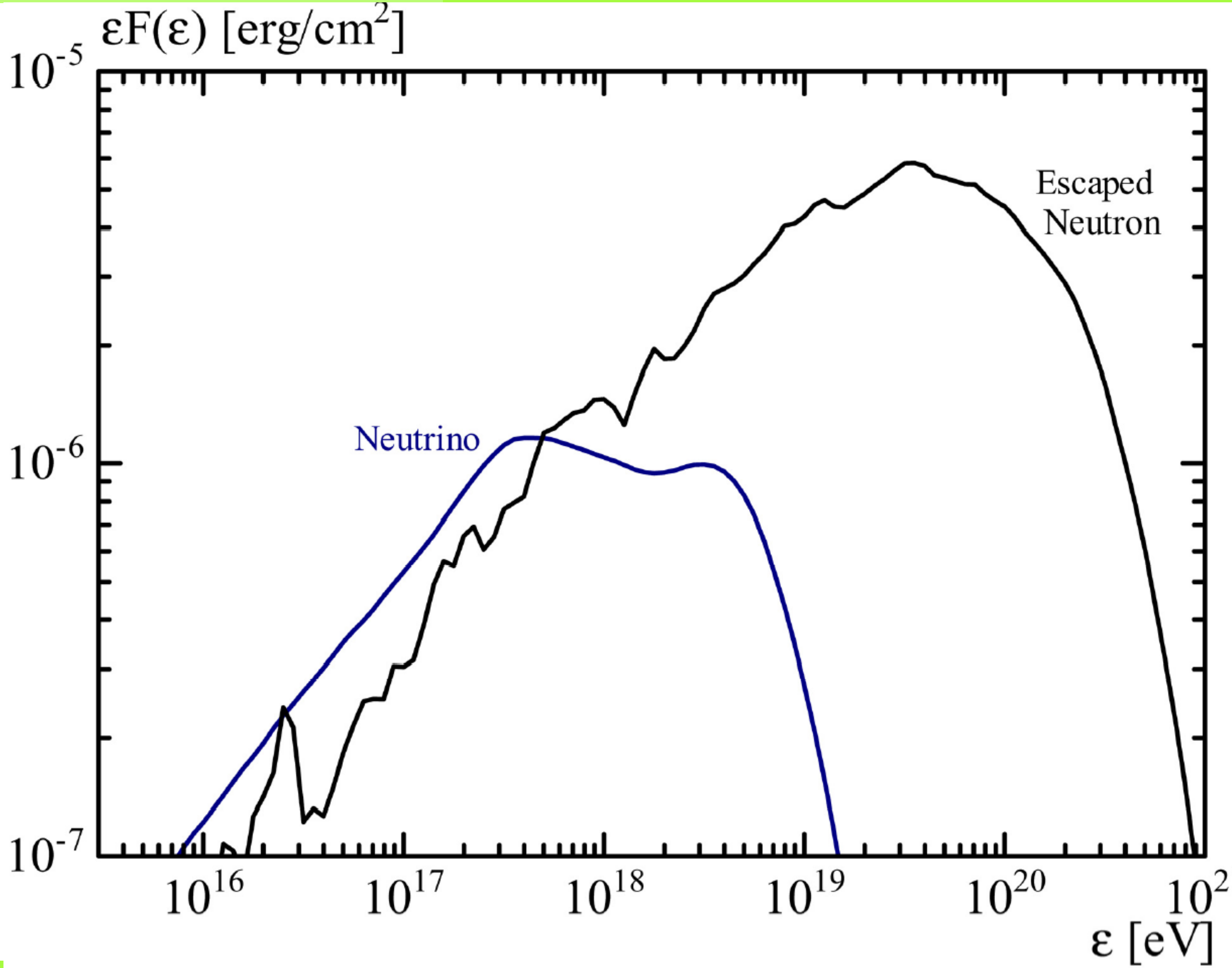
Asano & Meszaros in prep.

$R_0=10^{14}$ cm, Γ=800,
Ee=5×10^{50} erg, Ep=5×10^{51} erg,
$U_B/Ue=3$ ($B \propto R^{-2}$)
ε'_{min}=380 MeV

Note: particles are injected intermittently, so the injection time-step and refresh rate directly affect the output spectrum in the fast cooling particles. The time-step to follow cooling processes are short enough.

- Injected electrons emit synchrotron photons at 100eV.
- SSC component (100MeV) also grows as synchrotron photons increase.
- SSA and γγ cutoffs are seen.
- The maximum energy of protons grows with time owing to acceleration.
- Secondary neutrons, pions, muons, neutrinos also increase with time.
- After the end of particle injection, protons start to be cooled via adiabatic cooling. But, neutral particles keep their energies.
- Even in this stage, secondary particles are continuously produced, while the lepton model settles and high-energy electrons are not produced anymore.
- High energy neutrons keep creating pions so that neutrino production continues.

UHECR



$\varepsilon F(\varepsilon)$ [erg/cm^2]
10^{-5}
10^{-6}
10^{-7}
Escaped Neutron
Neutrino
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}
10^{21}
ε [eV]

Proton Synchrotron