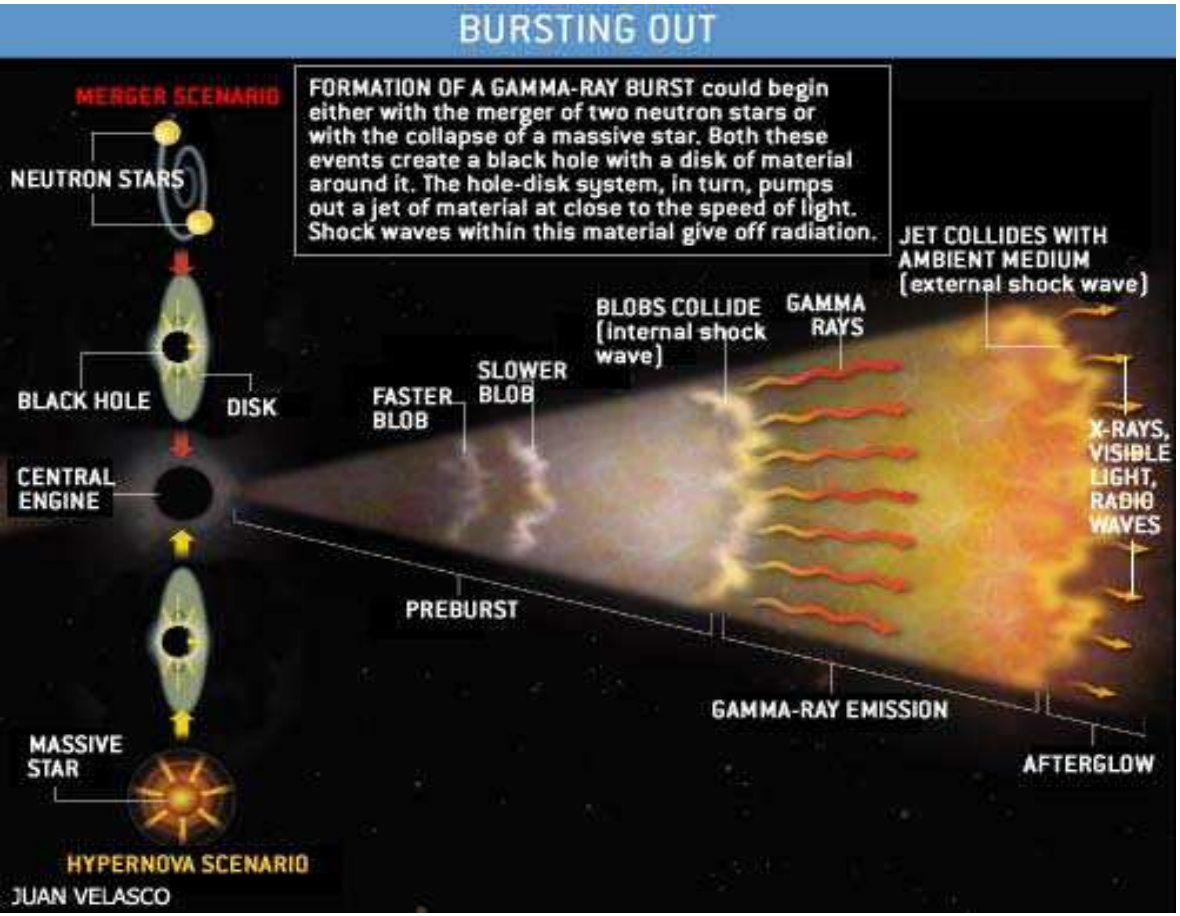
Acceleration and Emission in GRBs

Katsuaki Asano
(ICRR, Tokyo)

Gamma-Ray Burst as the origin of UHECRs

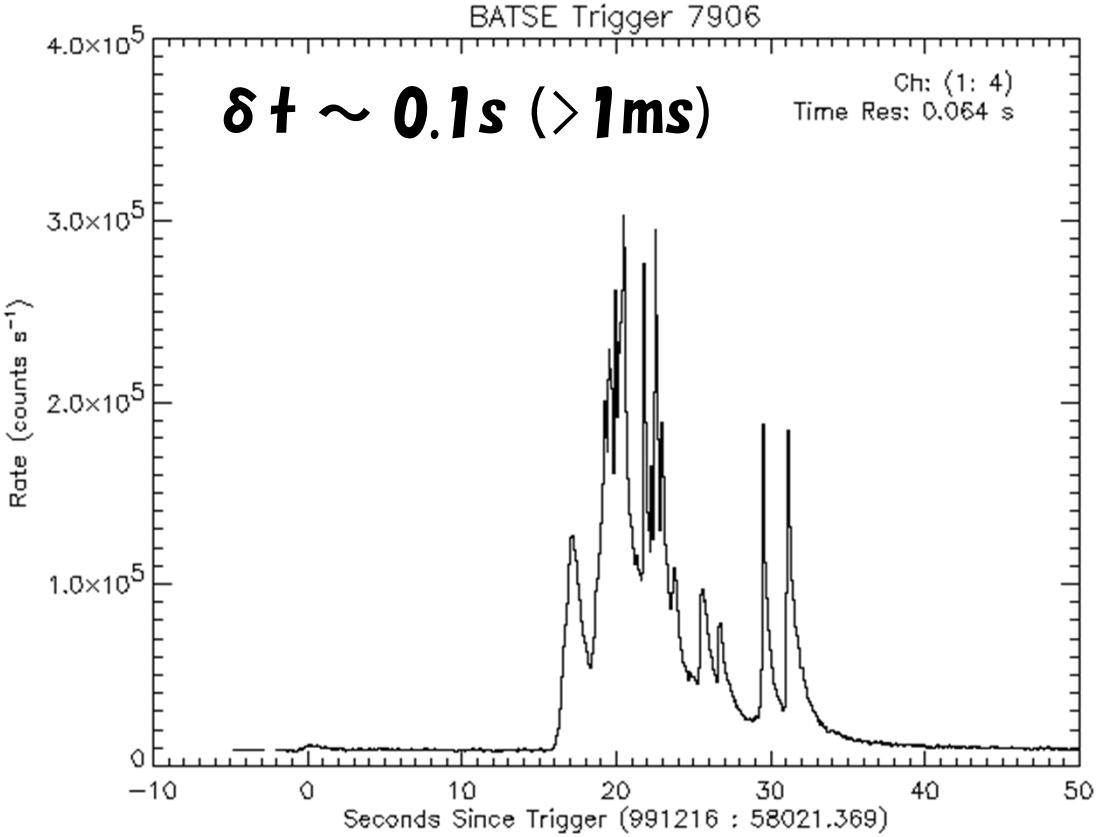


Death of a massive star/Binary merger
↓
Relativistic Outflow
↓
Dissipation → gamma-ray/CRs??

- **CR-acceleration & Emission mechanism** are tightly coupled.
- But, the gamma-ray emission mechanism is still veiled in mystery.
- First, I review several promising models for emission mechanism.
- Then, prospect of UHECR production will be discussed.

What we should explain

Lightcurve

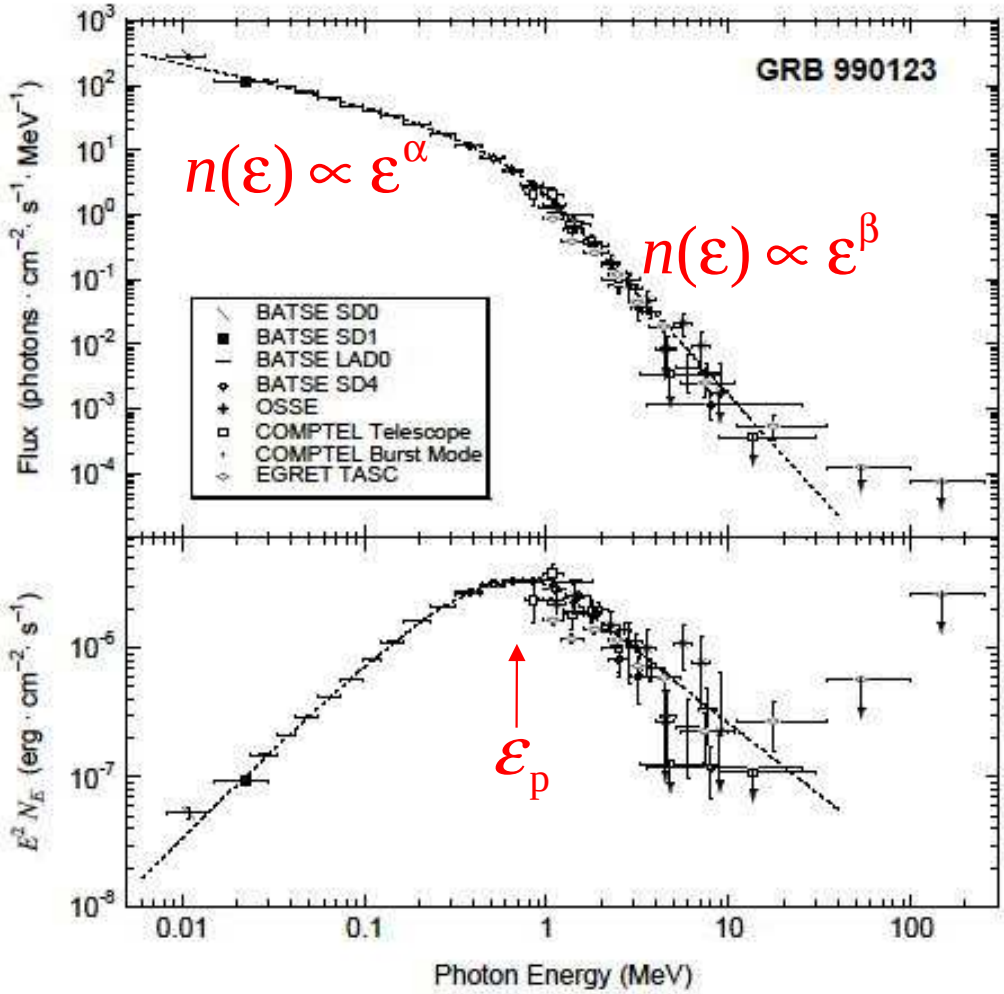


$\delta t \sim 0.1s$ (>1ms)

Luminosity

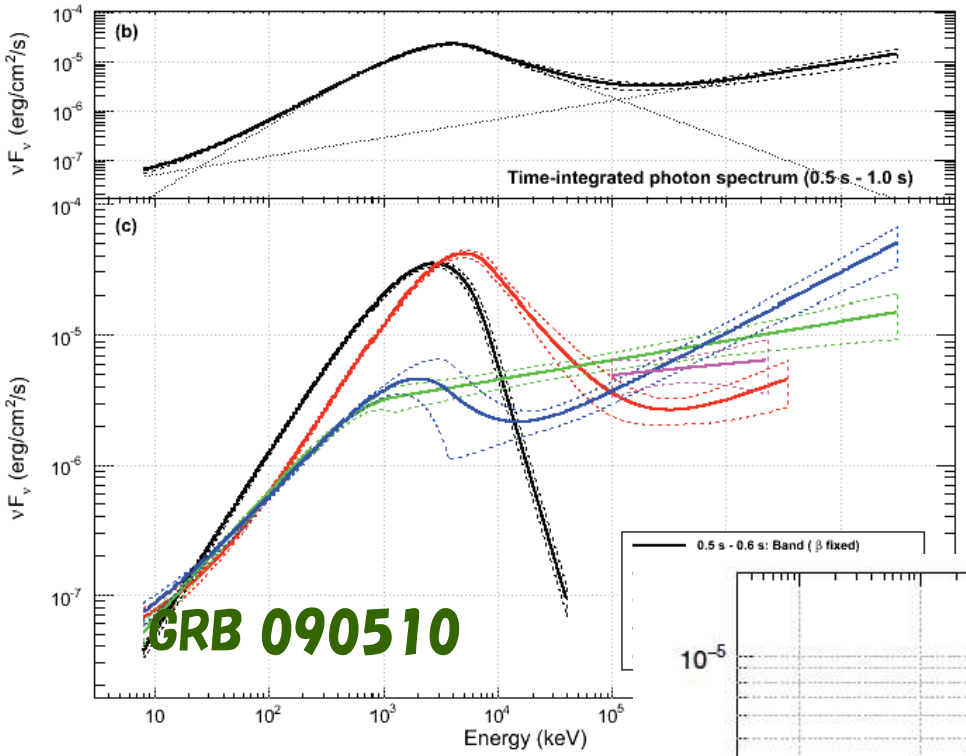
$\sim 10^{52}$ erg/s (10^{50}–10^{54} erg/s)

Spectrum

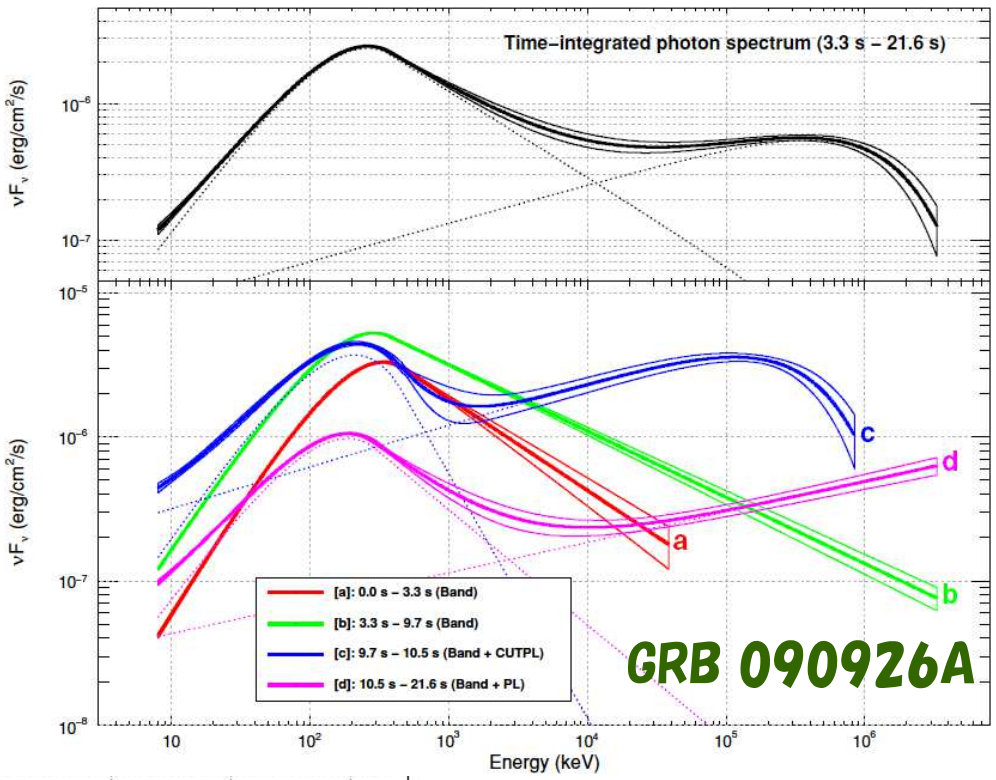


$$\alpha \approx -1, \beta \approx -2.2, \varepsilon_p \approx 500\text{keV}$$

Extra Spectral Components detected with Fermi

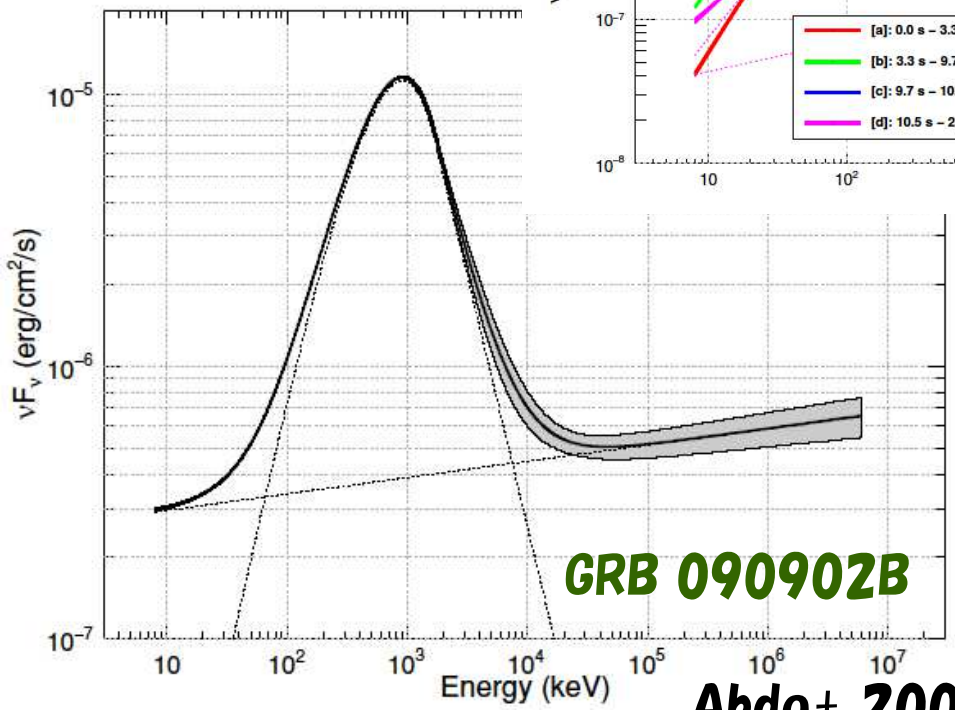


Ackermann+ 2010



Ackermann+ 2011

If GeV photons are due to hadronic emission, UHECR people are happy.



Abdo+ 2009

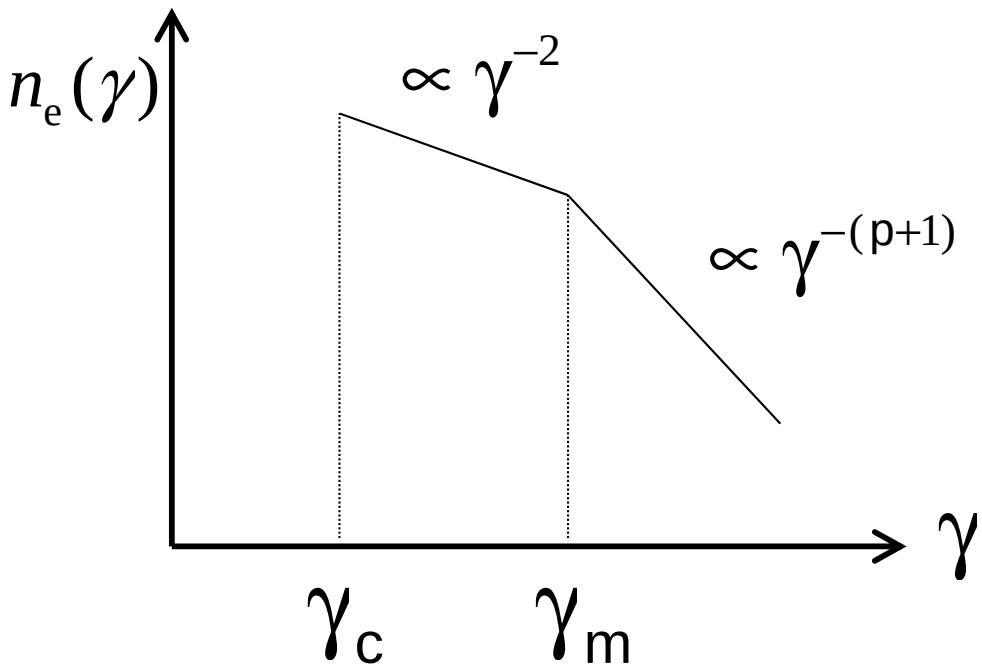
Models

- "Classical" Internal Shock
  - Shock acceleration + Synchrotron (Daigne, & many others)
  - Second order Fermi acc.? (Asano)
- (Dissipative) Photosphere (e.g. Pe'er, & many others)
  - Thermal emission + Hard tail
  - Gradual magnetic dissipation (Giannios etc.)
  - Shock/Turbulence near the photosphere (Rees & Meszaros etc.)
  - p-n collision (Beloborodov)
- Magnetic Dissipation
  - Reconnection switch (resistivity switch, McKinney & Uzdensky)
  - ICMART (shock induced, Zhang & Yan)

Internal Shock: acceleration+synchrotron

Emission radius

$$R \sim c\delta t\Gamma^2 > 10^{14}\,\mathrm{cm}$$

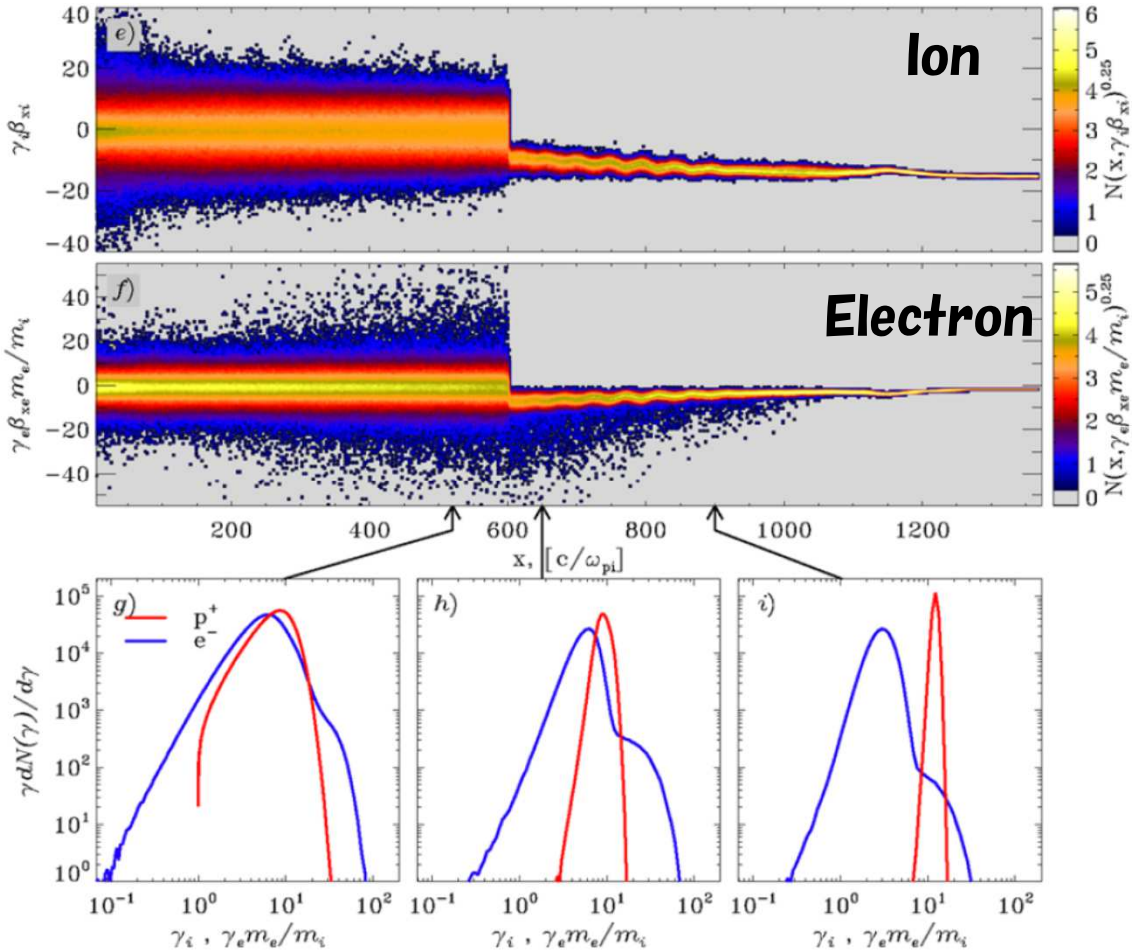


Minimum Lorentz factor at injection

$$\gamma_m = \varepsilon_e \frac{p-2}{p-1}\left(\frac{m_p}{m_e}\right)(\Gamma_{sh}-1)$$

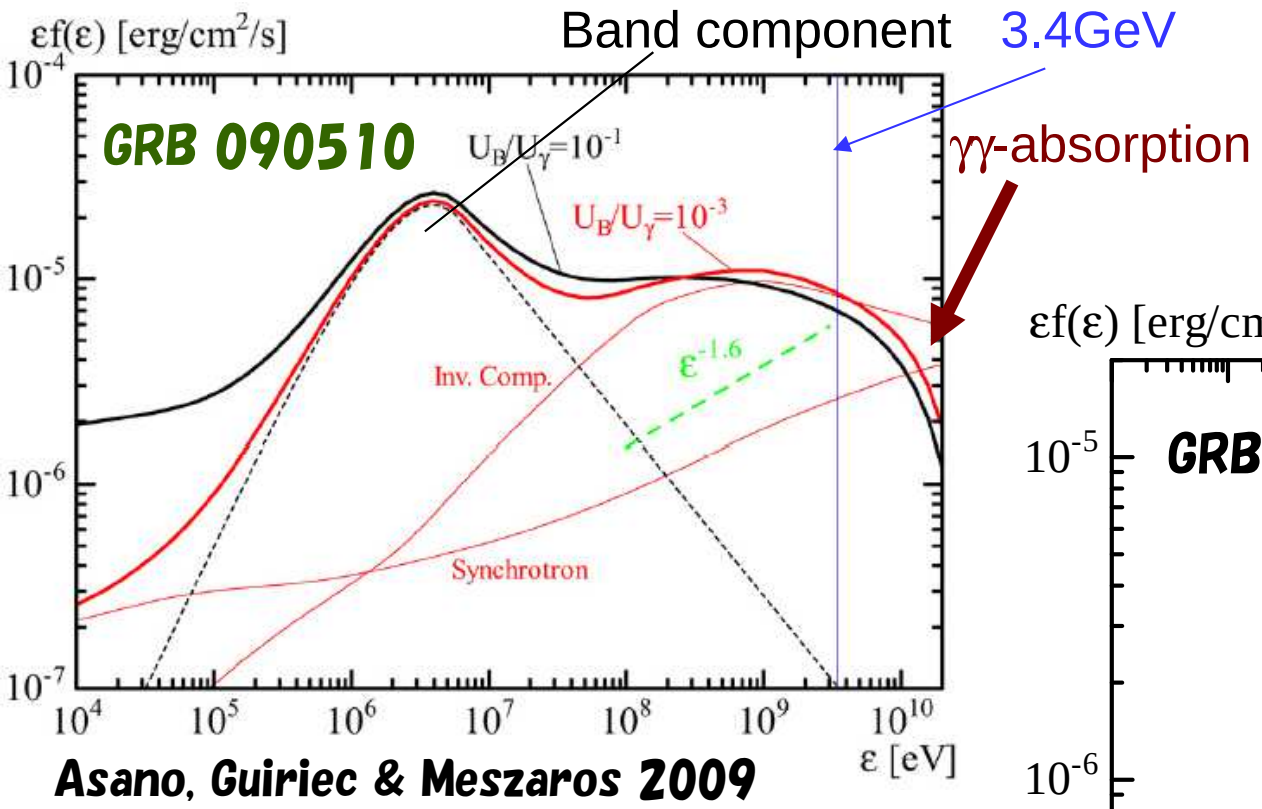
$$\approx 610\,\varepsilon_e(\Gamma_{sh}-1) >> \gamma_p \sim \Gamma_{sh}$$

Sironi & Spitkovsky 2011



Electron pre-heating due to synchrotron maser instability + wake field acceleration

Photon signature of proton acceleration



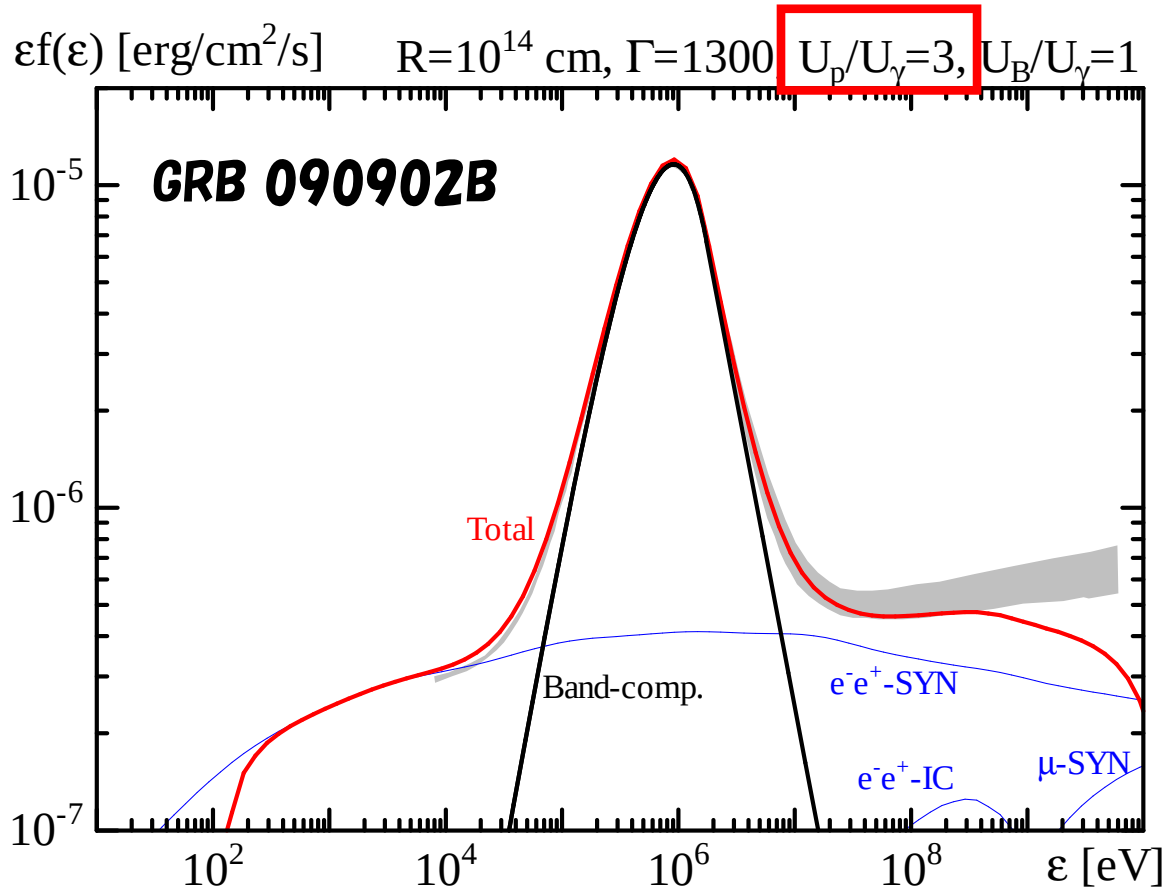
Asano, Guiriec & Meszaros 2009

R=10^{14} cm

Γ=1500

$U_B / U_\gamma = 10^{-3}$

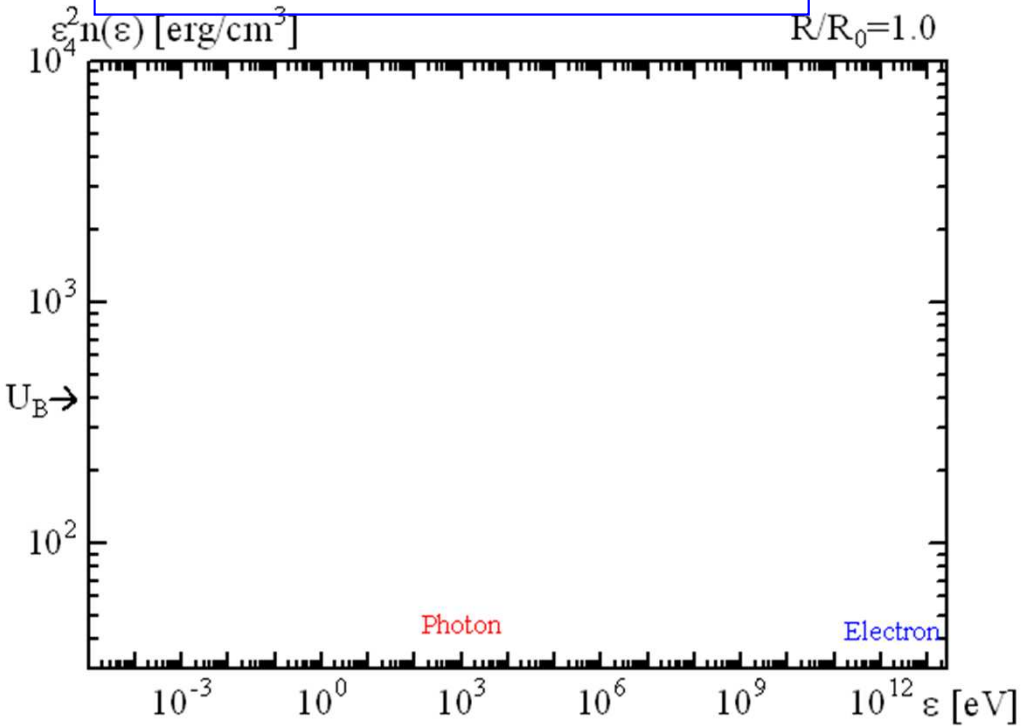
$L_p / L_\gamma = 200$

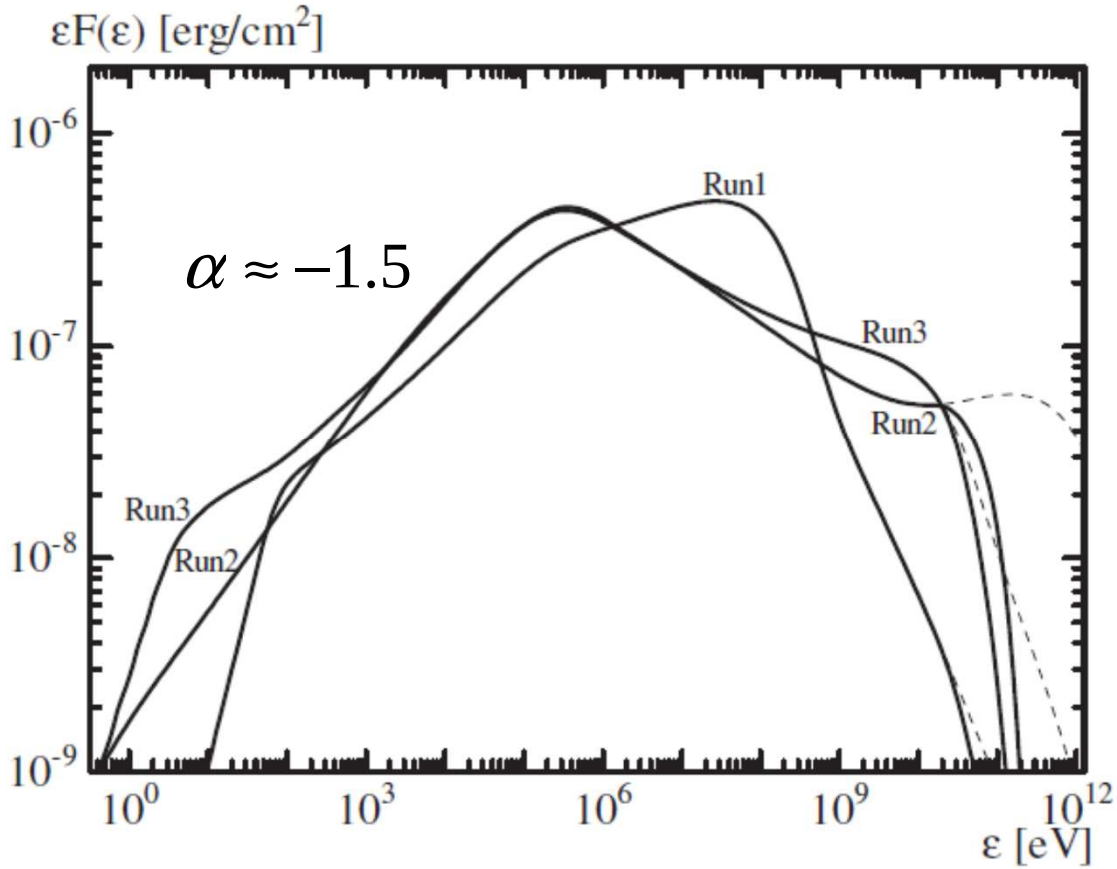


Asano, Inoue and Meszaros 2010

Problem in synchrotron model

Time-dependent simulation
Spectra in the shell frame





Asano & Meszaros 2011

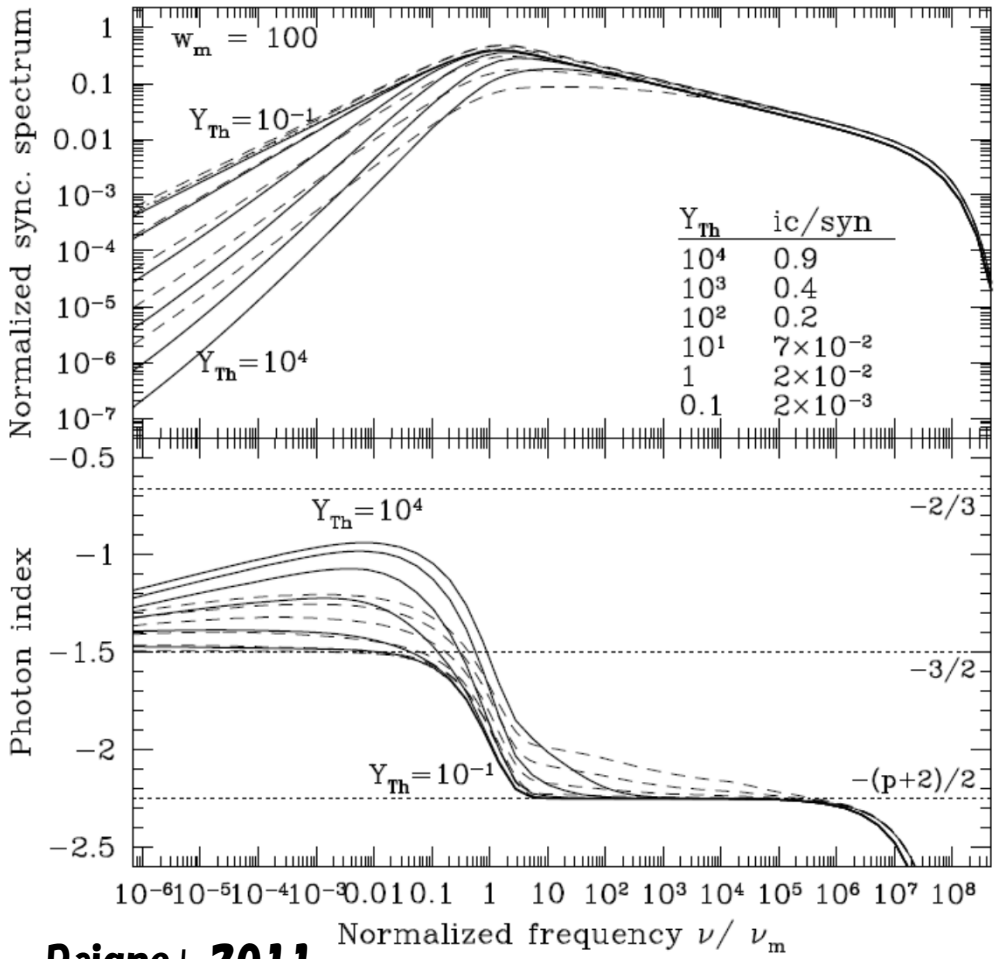
$R_0 = 6\times10^{15}$ cm, $\Gamma = 1000$,
$B' = 100$G, $E_e = 10^{54}$ erg,
$\gamma'_{min} = 11.3$ GeV

Cooled electrons emit soft photons.
The low-energy index becomes too soft!

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

To harden the spectrum

IC cooling with Klein-Nishina effect



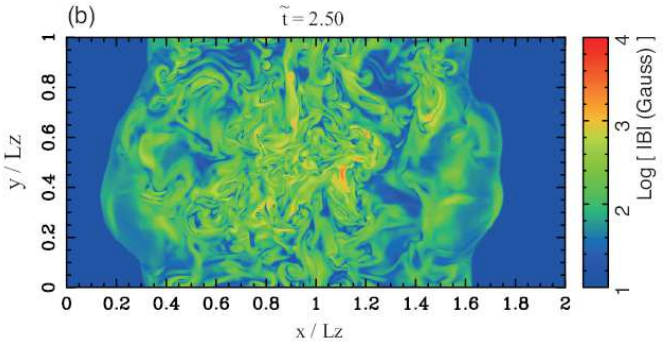
Daigne+ 2011

$$Y_{Th} = \frac{p-2}{p-1}\frac{\epsilon_e}{\epsilon_B}$$

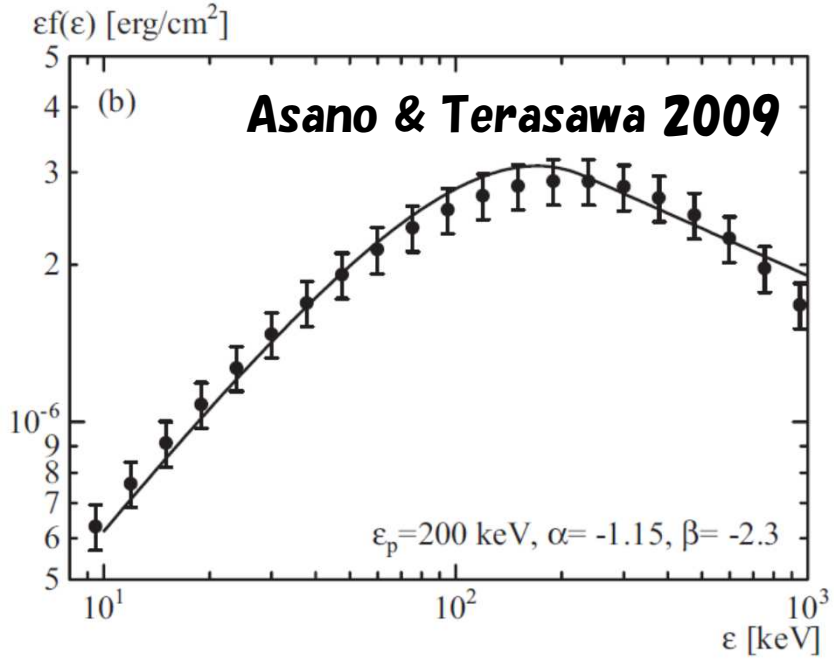
IC cooling prevents soft Syn. emission.

2nd order Fermi acceleration

Inoue, Asano, Ioka 2011



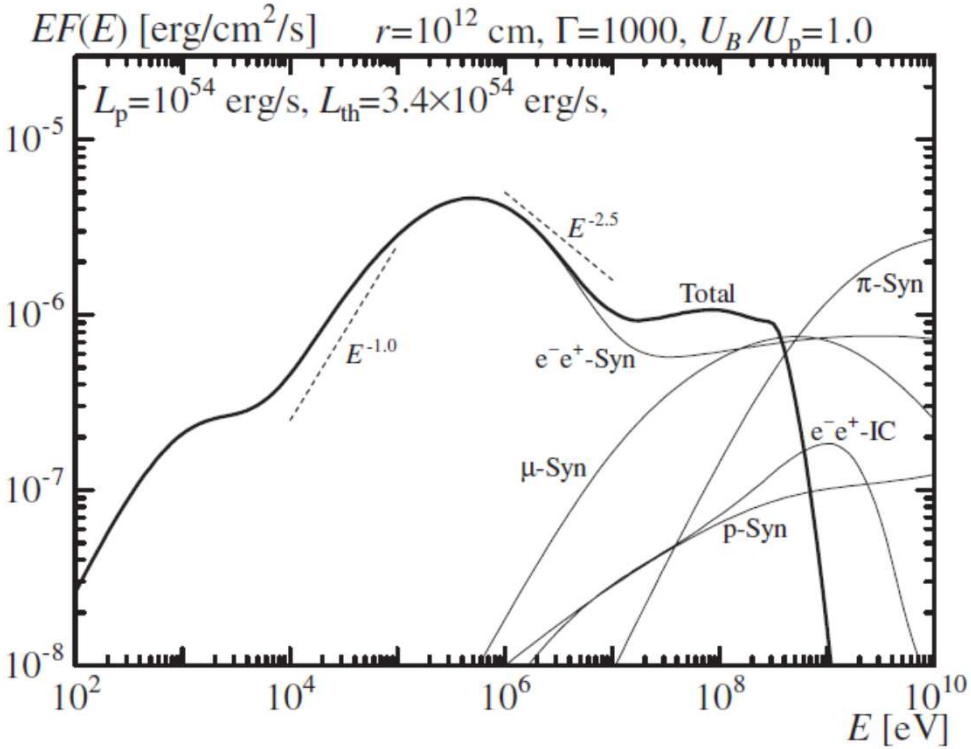
Shock
→turbulence



Continuous acceleration prevents electron cooling.

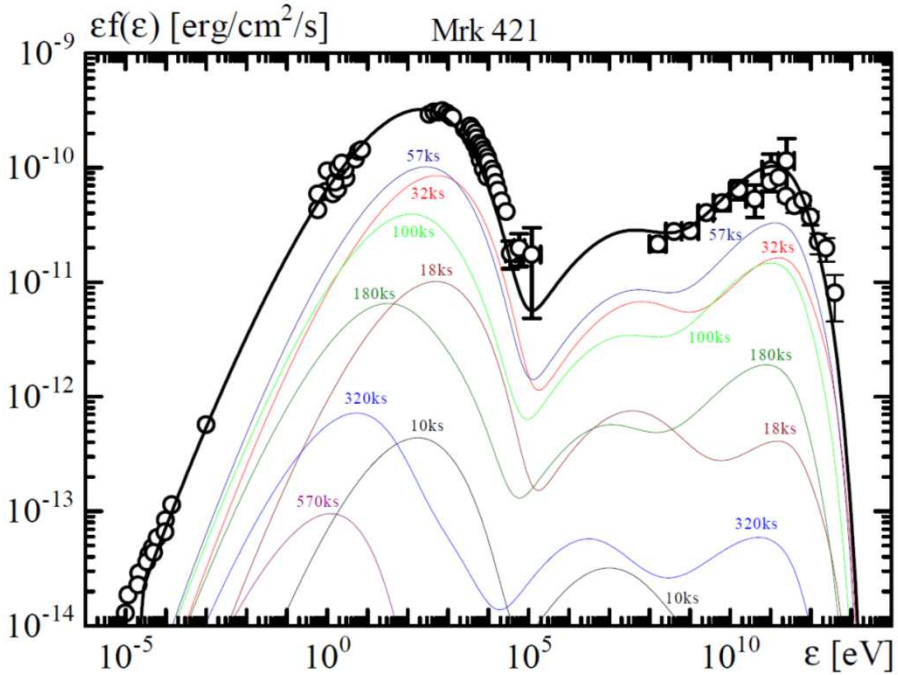
2'nd order Fermi acceleration

Proton: Shock acceleration
Electron: Injected via hadronic cascade
→re-accelerated by turbulence



Murase, Asano, Terasawa, Meszaros 2012

Even for AGNs…



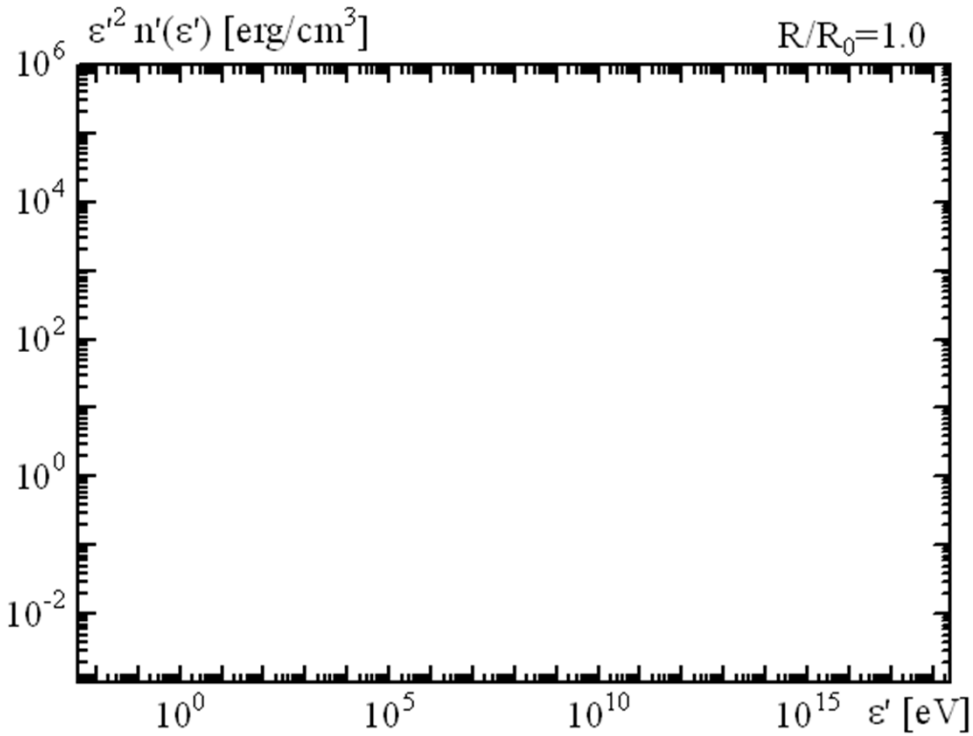
Asano, Takahara, Kusunose, Toma, & Kakuwa 2013

UHECR production is expeted in this model.

See also Stawarz & Petrosian 2008 etc.

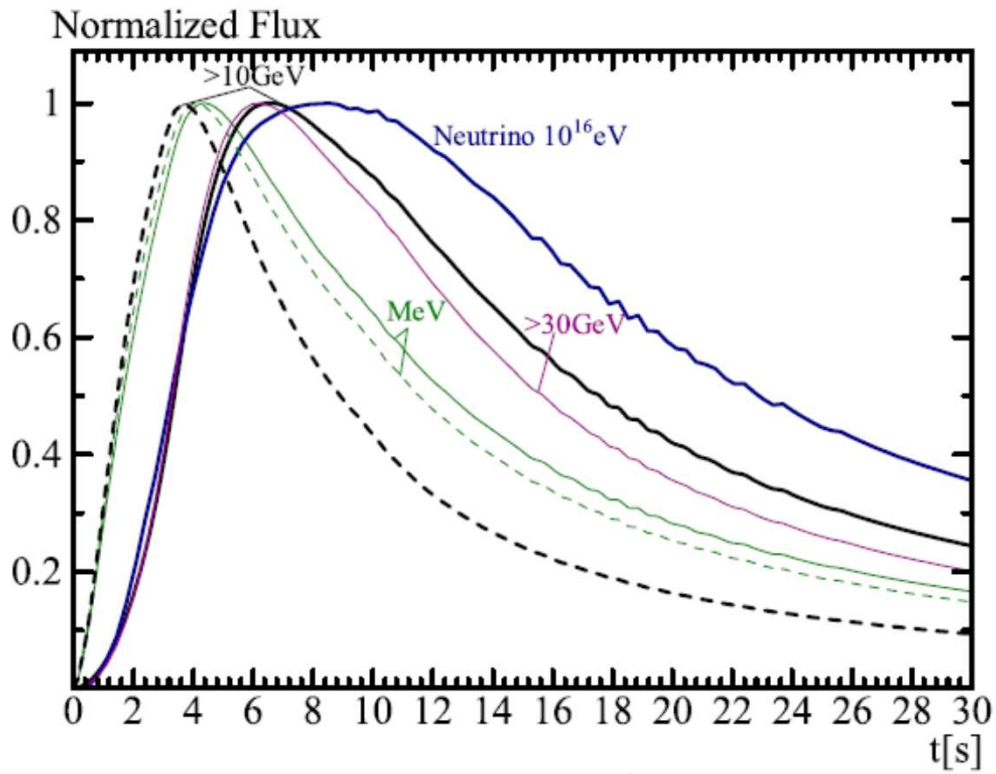
Hadronic cascade

Time-dependent simulation



Asano & Meszaros 2012

$R_0 = 10^{15}$ cm, $\Gamma = 800$,
$E_e = 10^{52}$ erg, $E_p = 10^{53}$ erg,
$U_B/U_e = 0.1$ ($B \propto 1/R$)
$\varepsilon'_{min} = 1.4$ GeV



Broad and delayed light curve in GeV-TeV range.
→ Hadronic signature

CTA can check this!

Photosphere model

Escape of thermal photons from the photosphere

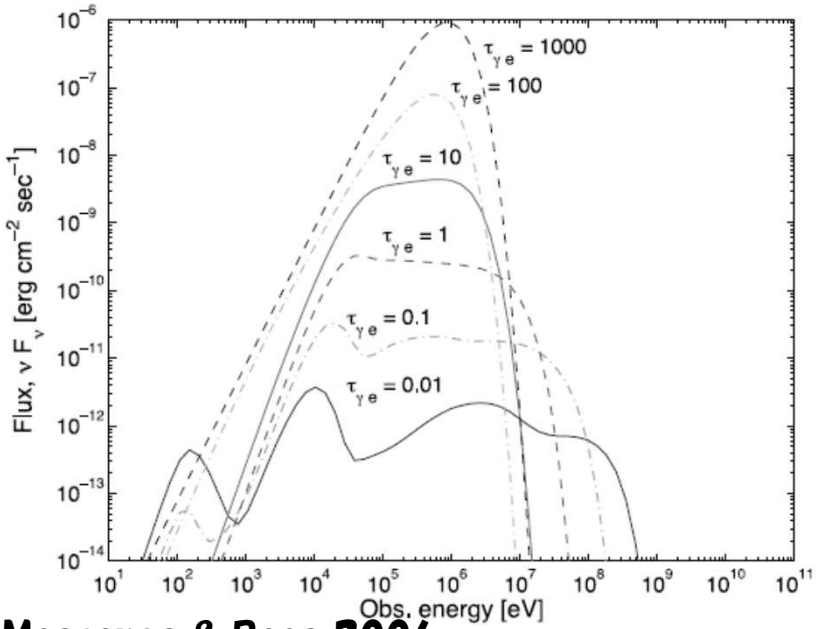
Emission radius

Baryonic Jet $\Gamma \propto r$

$$R_{\rm ph} = \frac{L_{\rm iso}\sigma_{\rm T}}{4\pi\eta^3 m_{\rm p} c^3} \simeq 1.2\times10^{13}\left(\frac{\eta}{100}\right)^{-3}\left(\frac{L_{\rm iso}}{10^{52}{\rm erg/s}}\right){\rm cm}$$

Poynting-flux dominated Jet $\Gamma \propto r^{1/3}$

$$\frac{r_{\rm ph}}{r_0} = \left(\frac{L\sigma_T}{4\pi m_p c^3 r_0}\right)\frac{1}{\eta\Gamma^2} = \eta_T^6\frac{1}{\eta\Gamma^2}$$



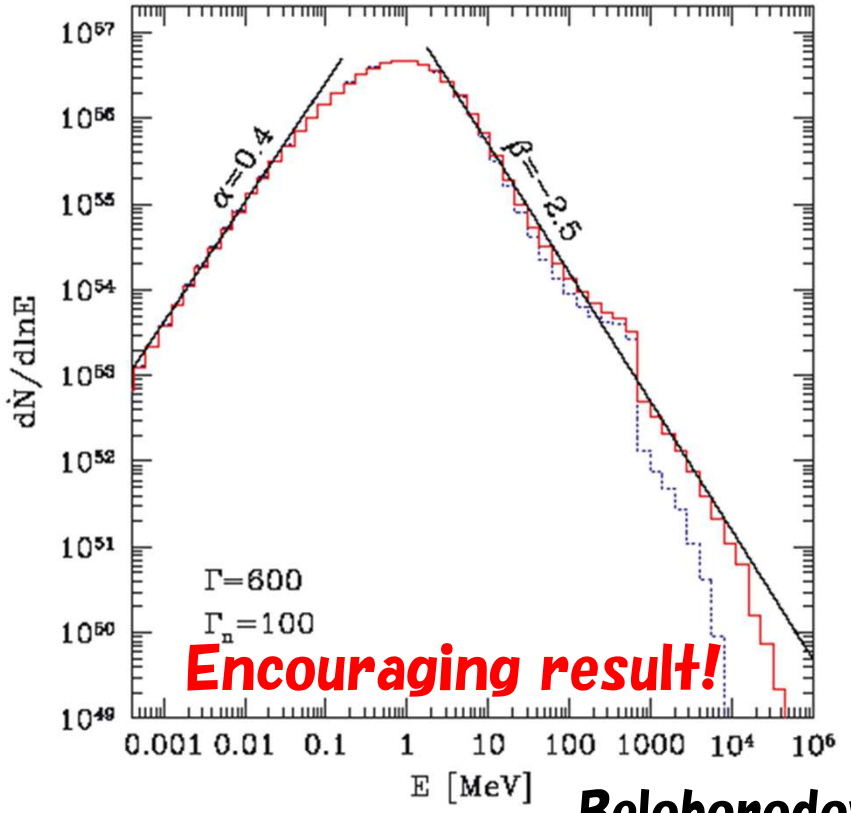
Pe'er, Meszaros & Rees 2006

- If η is high enough, most of the jet energy is released as thermal photons.
- The peak energy ε_p corresponds to the initial photon temperature.

Good to explain ε_p and high-efficiency.
The low-energy index becomes too hard!
Dissipative contribution is required to make non-thermal spectra.

Collisional model

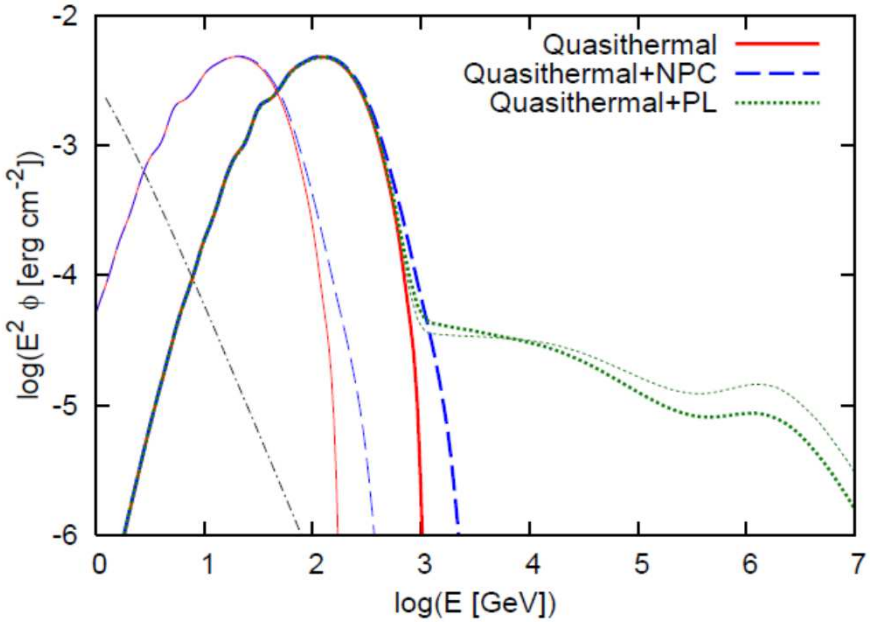
Collision of proton and neutron fluids leads to hadronic cascade
→high-energy emission



Encouraging result!

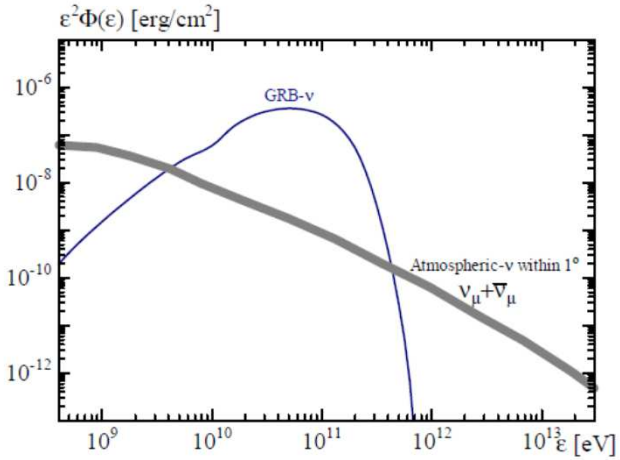
Beloborodov 2010

Neutrino spectrum



Murase, Kashiyama & Meszaros 2013

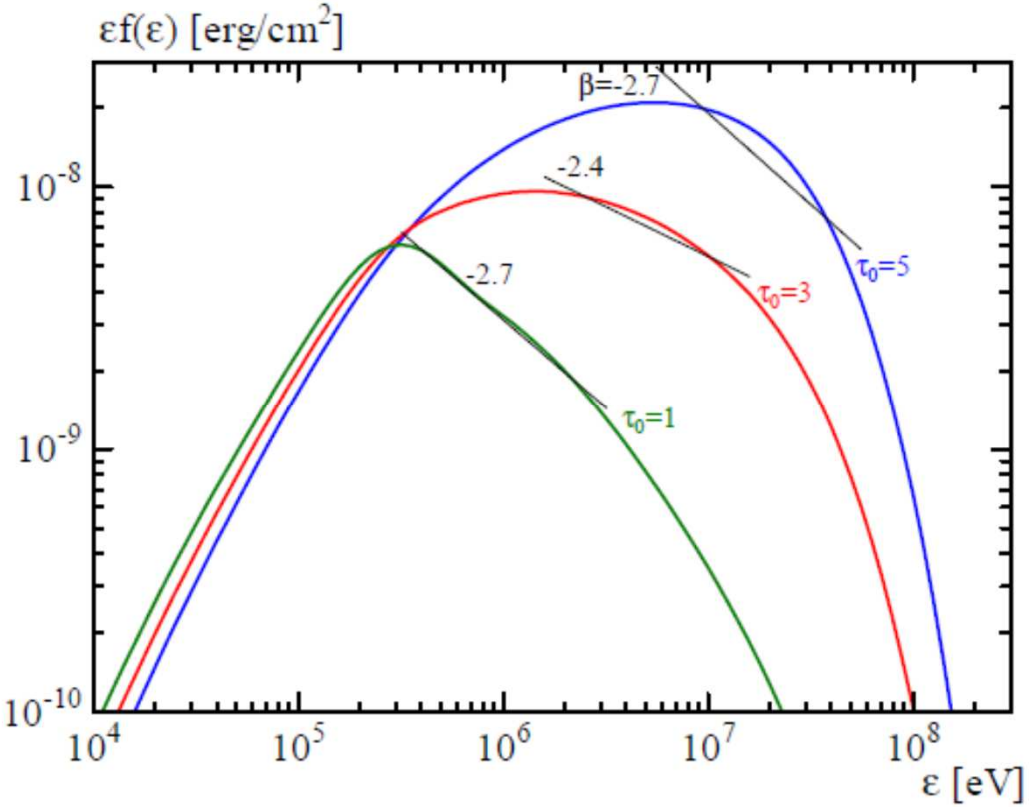
See also Bartos+ 2013, Asano & Meszaros 2013



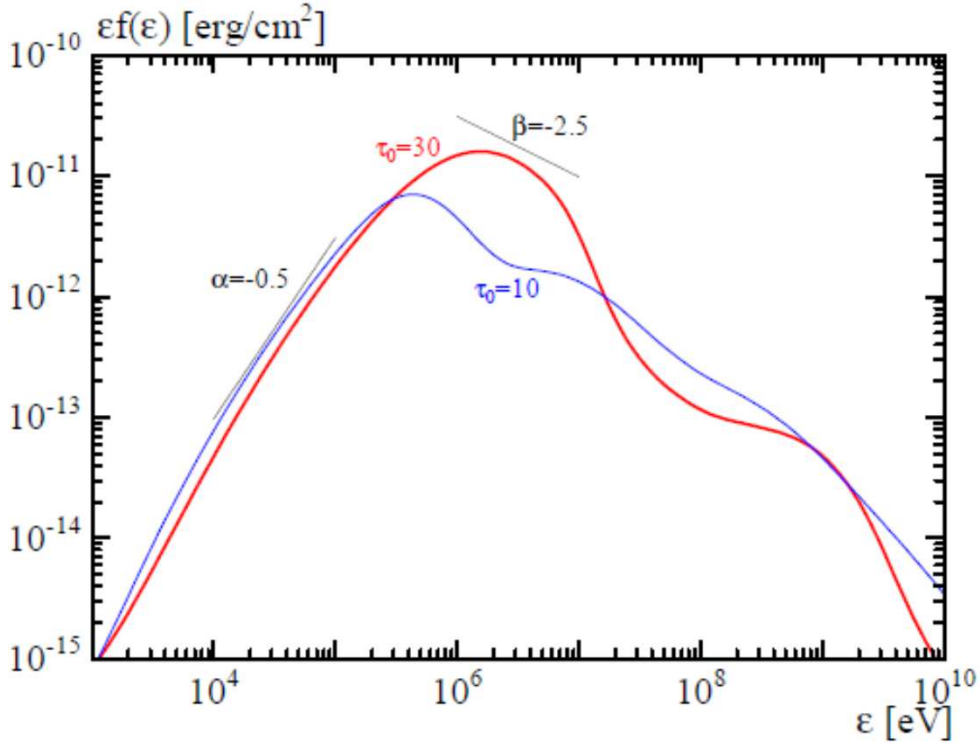
Parameter dependence

In models with energy dissipation around the photosphere, the spectra largely depend on the parameters…

Electron heating around the photosphere.



Collisional model



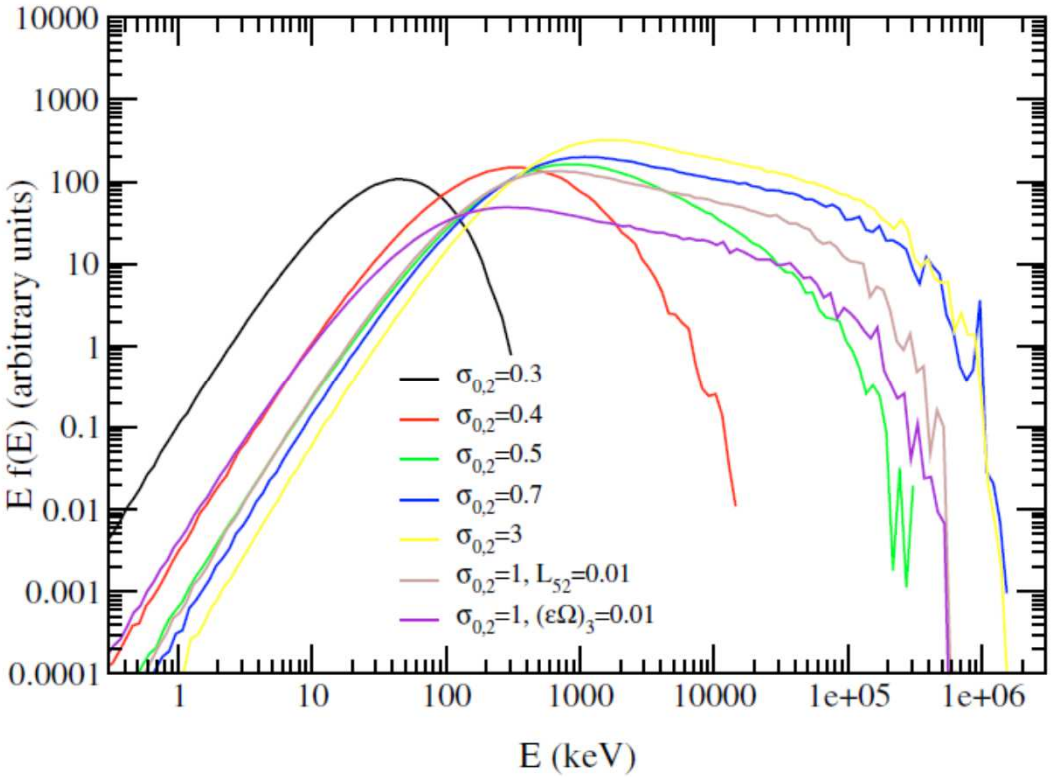
Optical depth dependence
Asano & Meszaros 2013

Magnetic dissipation

Gradual energy dissipation

$$P_{\rm diss} = \frac{B'^2/8\pi}{t_{\rm dec}/2} = \frac{1.5\times10^{15}}{r_{11}^3}\frac{L_{52}}{\sigma_{0,2}^{3/2}} \quad {\rm erg\,cm^{-3}\,s^{-1}}$$

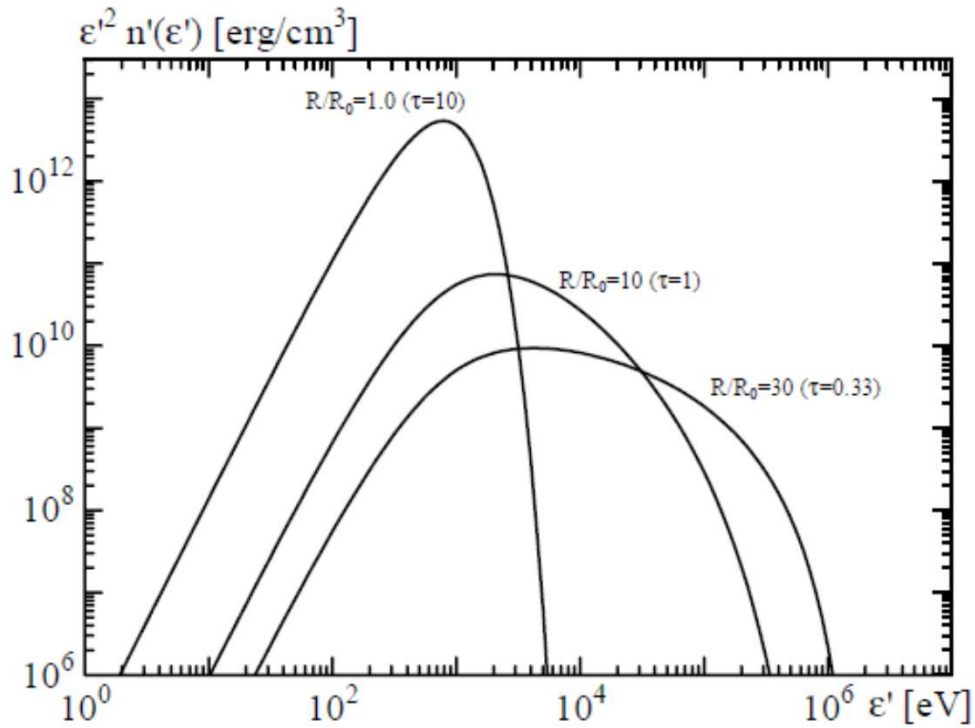
Giannios & Spruit 2007



Temperature increases with radius

$$T_{\rm e} = 2.0 r_{11}^{5/3} f_{\rm e,1} \frac{(\varepsilon\Omega)_3^{2/3}\sigma_{0,2}^{5/2}}{L_{52}} \quad {\rm keV}$$

Similar to a model with continuous heating ($T \propto r$)



Asano & Meszaros 2013

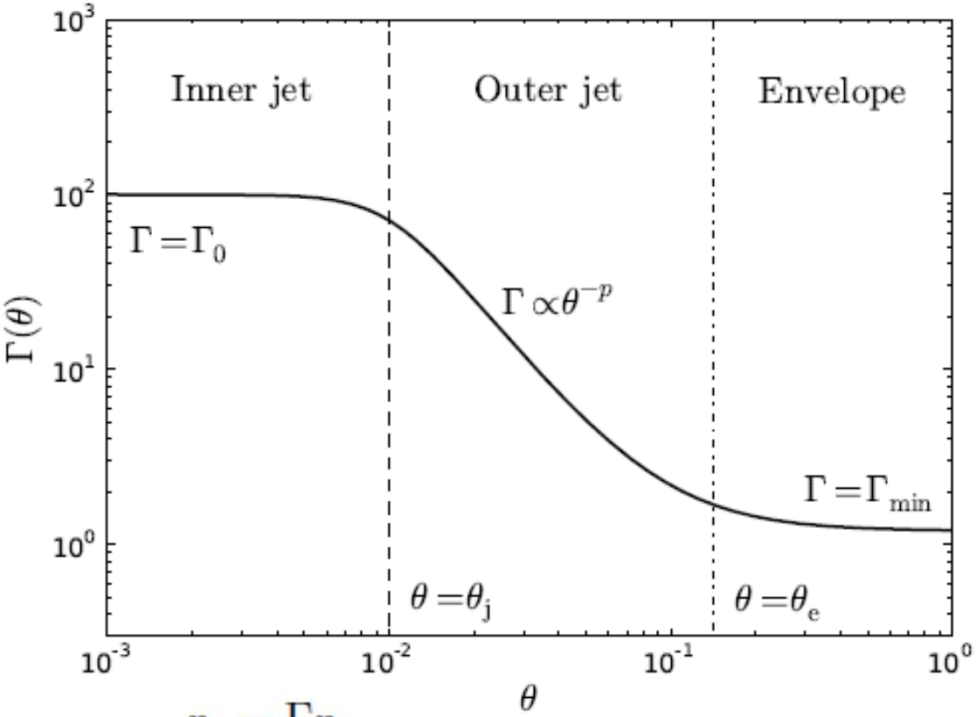
Energy injection in a wide range of radius!

Problems

To soften the spectrum…

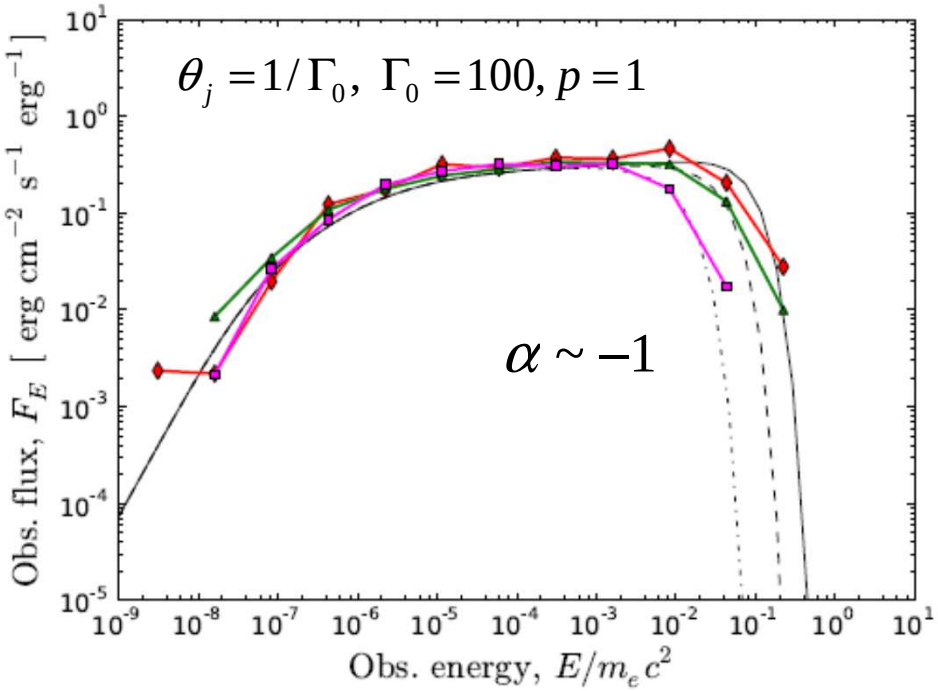
Contribution of off-axis emission

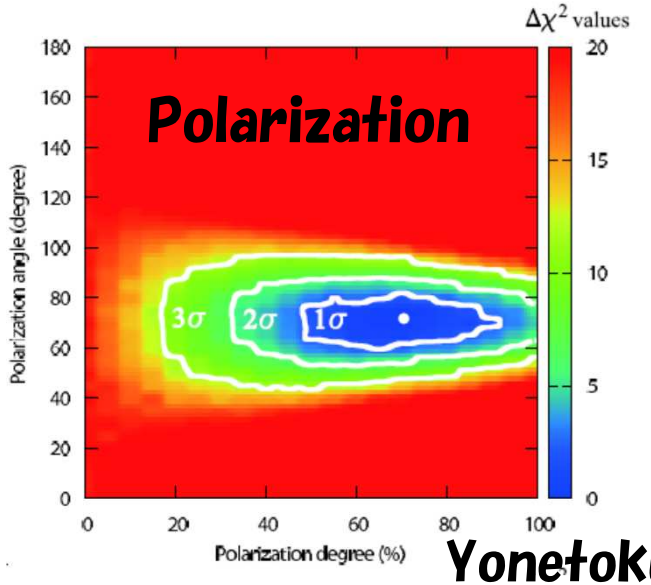
Lundman, Pe'er & Ryde 2012



$$r_s = \Gamma r_0$$

$$T'(\theta, r) = T_0(r_0/r_s(\theta))(r_s(\theta)/r)^{2/3}$$





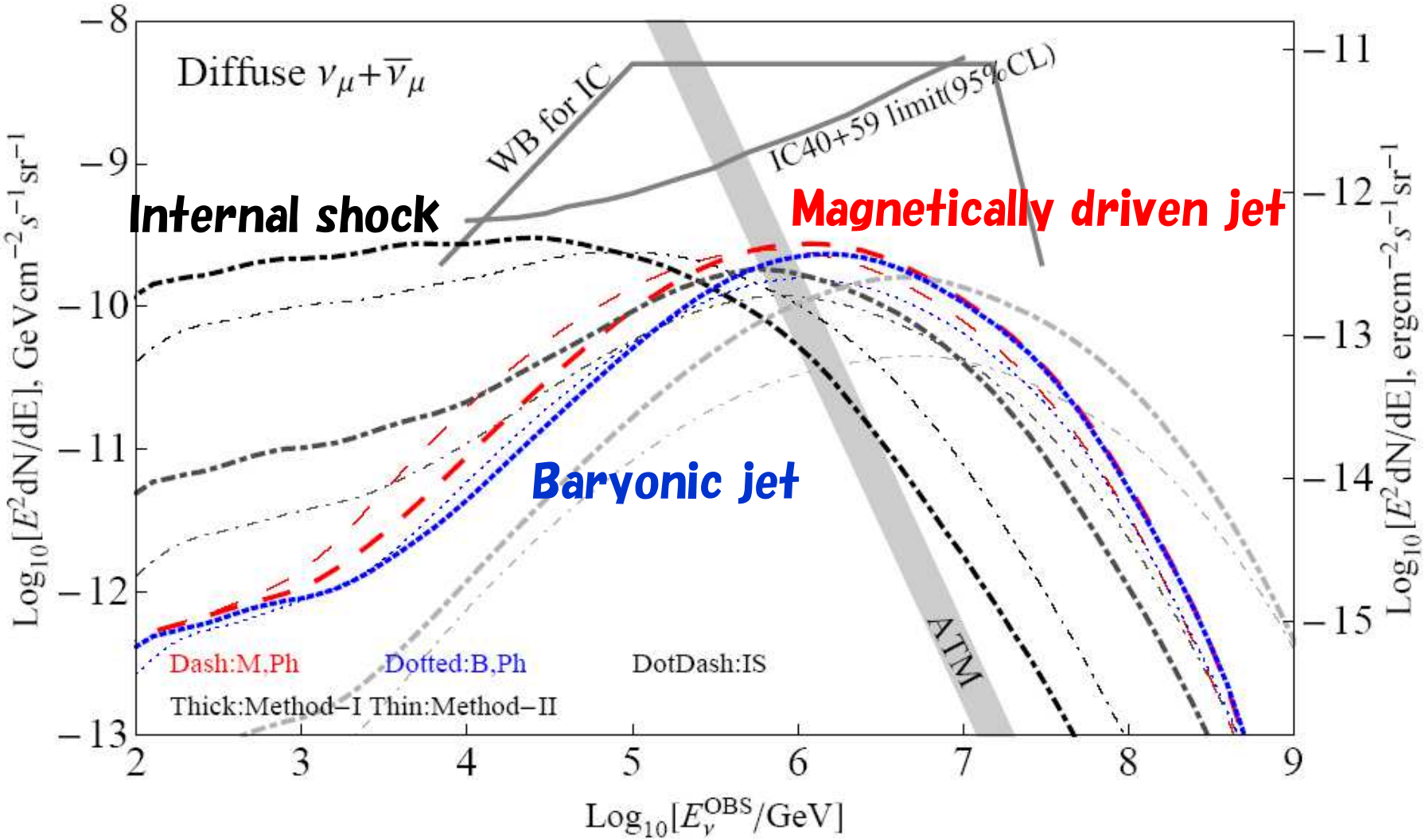
Yonetoku+ 2012

A narrow structure of $\theta \sim 1/\Gamma$ is required.

Neutrinos from photosphere

Gao, Asano, Meszaros 2012

Recent detection of 2 neutrinos

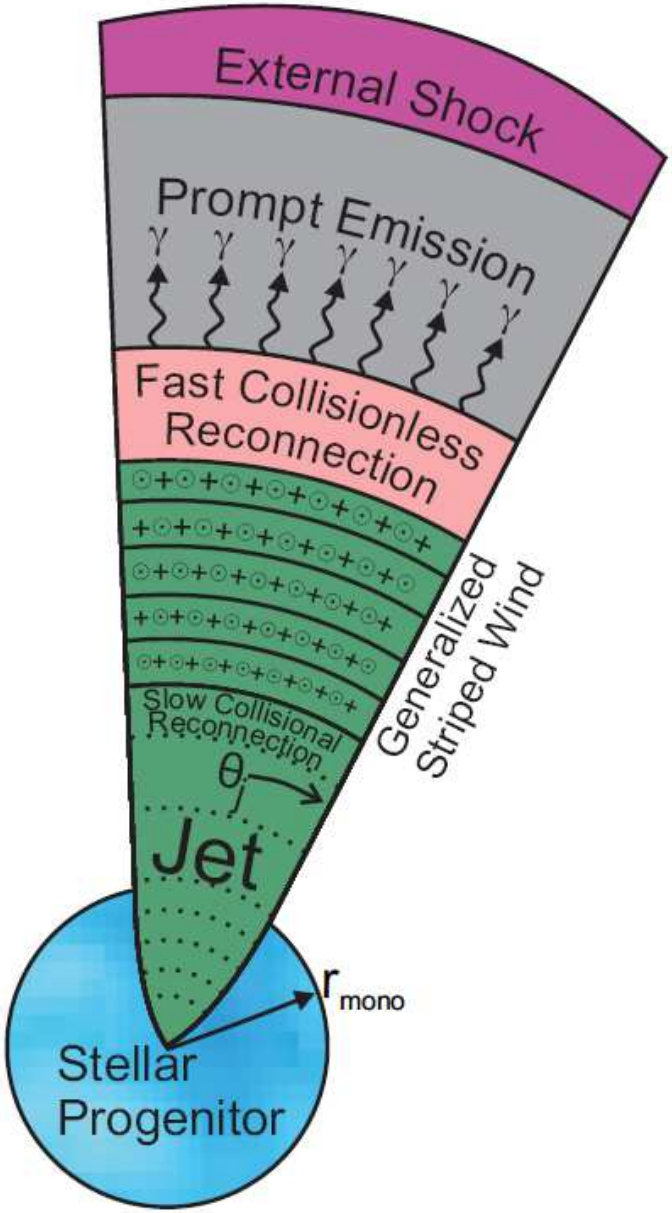


Proton acceleration at the photosphere → neutrinos due to $pp/p\gamma$

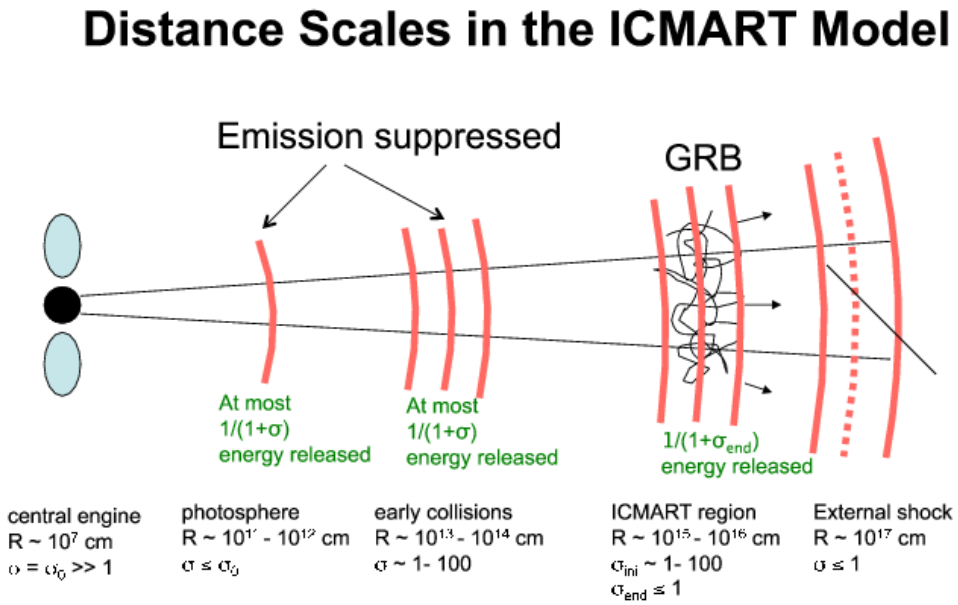
The equipartition leads to low neutrino flux.

Magnetic dissipation model

Mckinney & Uzdensky 2012



ICMART: Internal-Collision-Induced Magnetic Reconnection and Turbulence



Zhang & Yan 2011

Most of magnetic energy will be dissipated.
B goes to bulk kinetic energy?
How efficient in radiation?

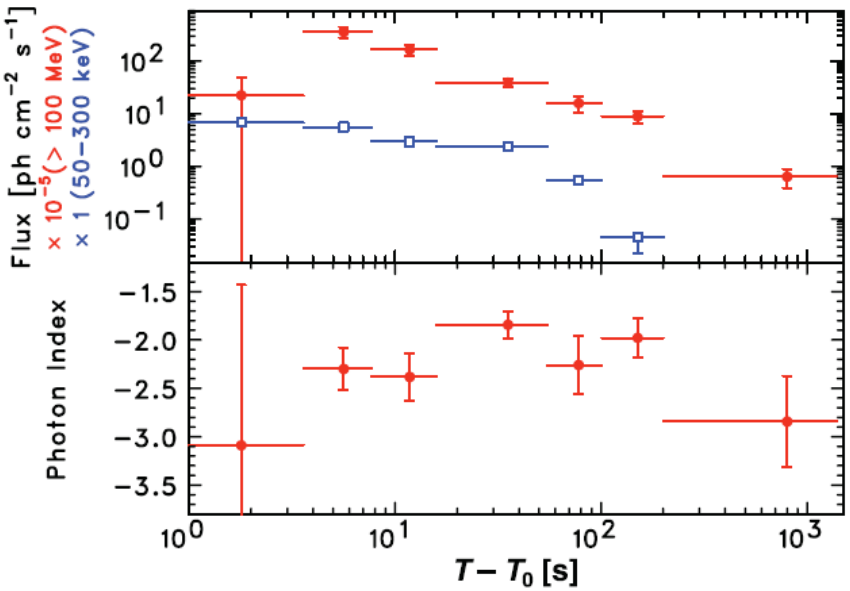
Almost "Assumption"="Conclusion"…

GeV afterglow

Usual X-ray and optical afterglow may be due to synchrotron radiation from external shocks propagating ISM.

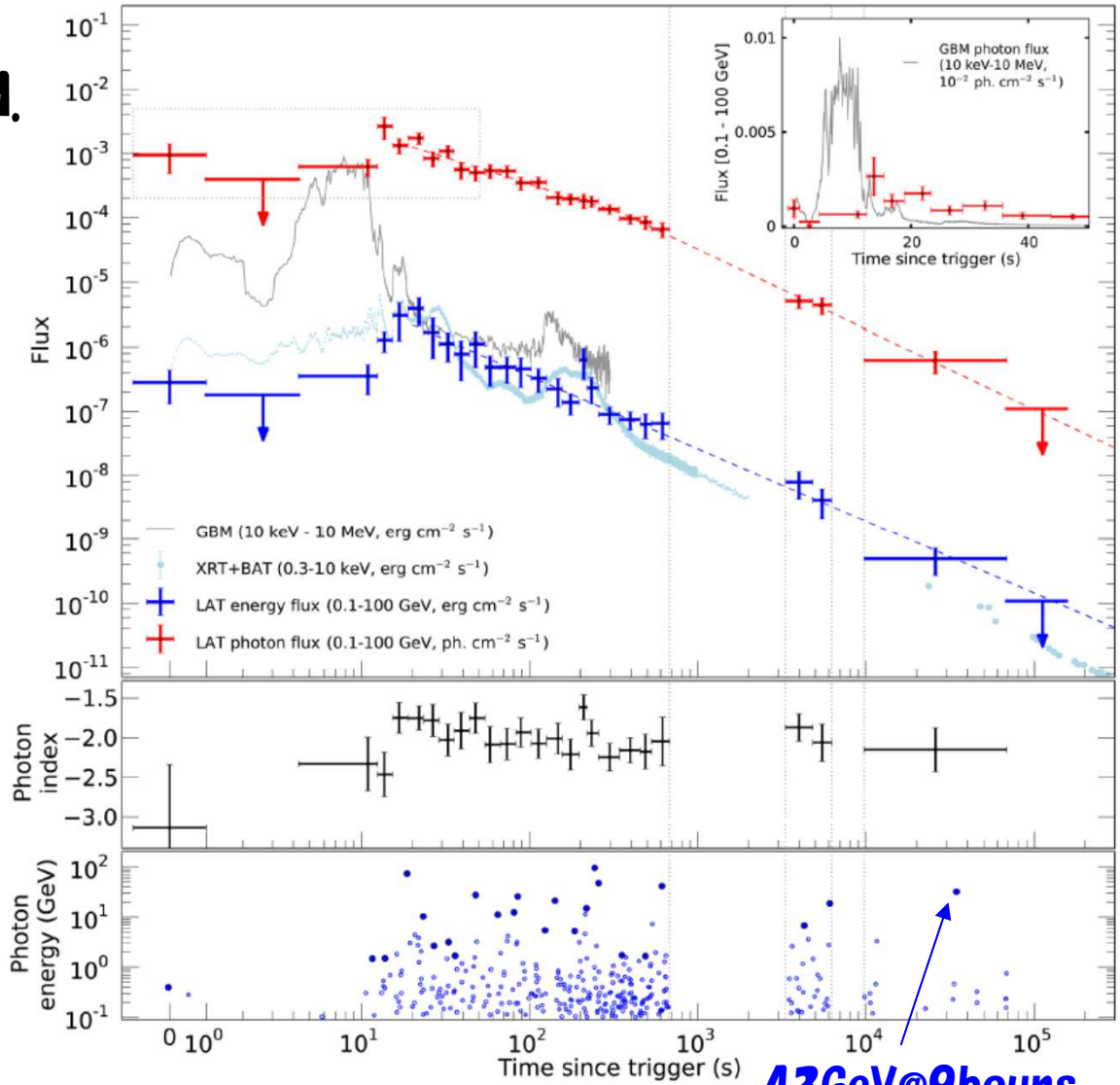
GeV afterglow is the same?
(Ghisselini+, Kumar+)

GRB 080916C Abdo+ 2009



Hard spectrum!

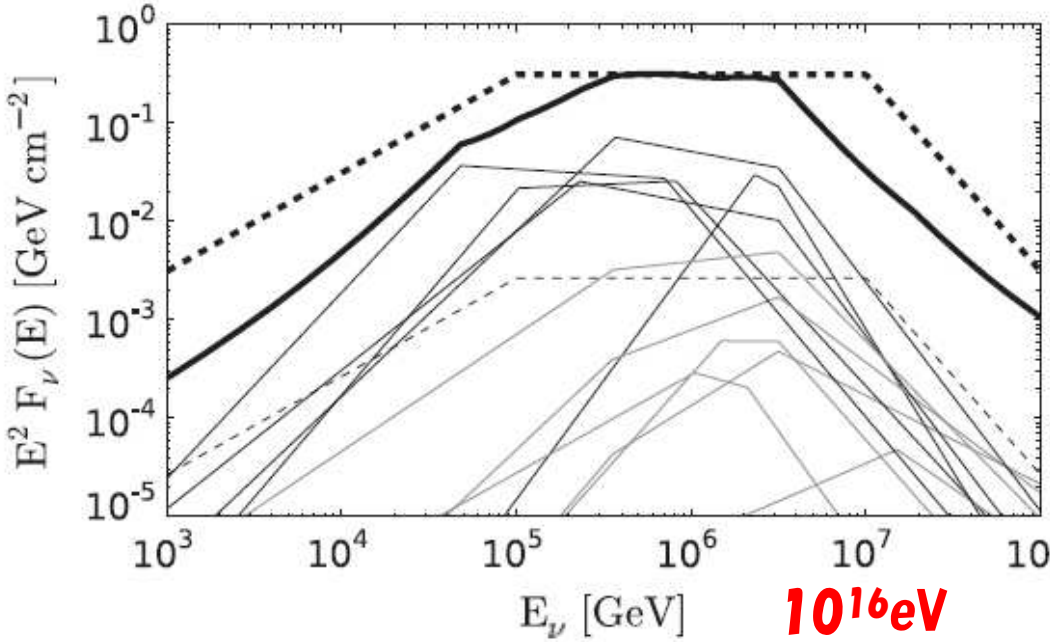
GRB 130427A (Ackermann+ 2013)

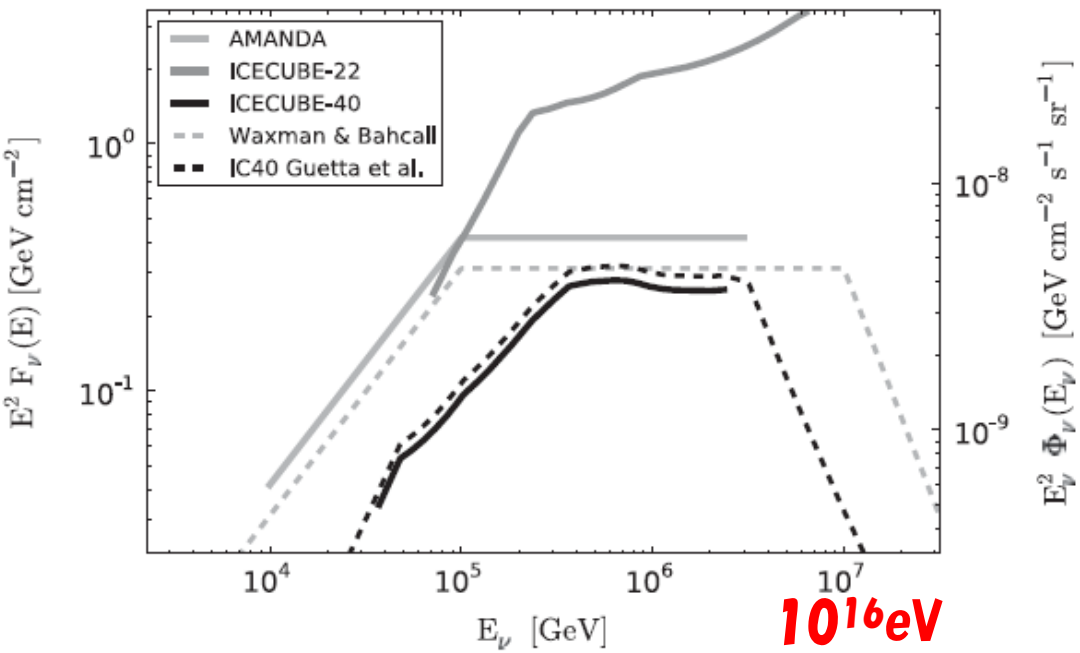


43GeV@9hours

Synchrotron maximum energy 79 $\Gamma(t)$ MeV

Upper limit on proton acceleration by IceCube





Abbasi+2011

- "Benchmark" = Γ = 300, δt = 10ms, L_p/L_γ = 10

→ Not UHECR source??

The model in IceCube is too rough

The Astrophysical Journal, 752:29 (10pp), 2012 June 10 doi:10.1088/0004-637X/752/1
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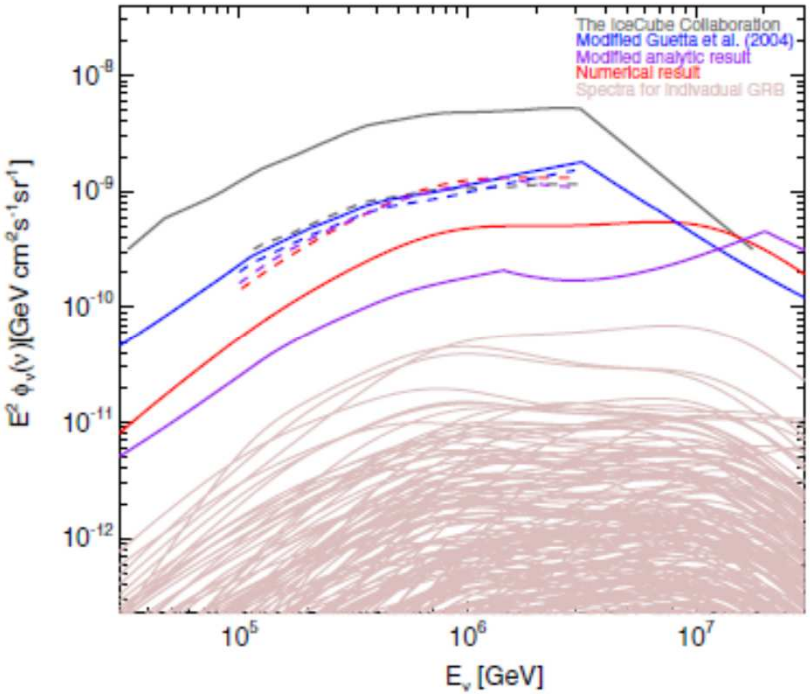
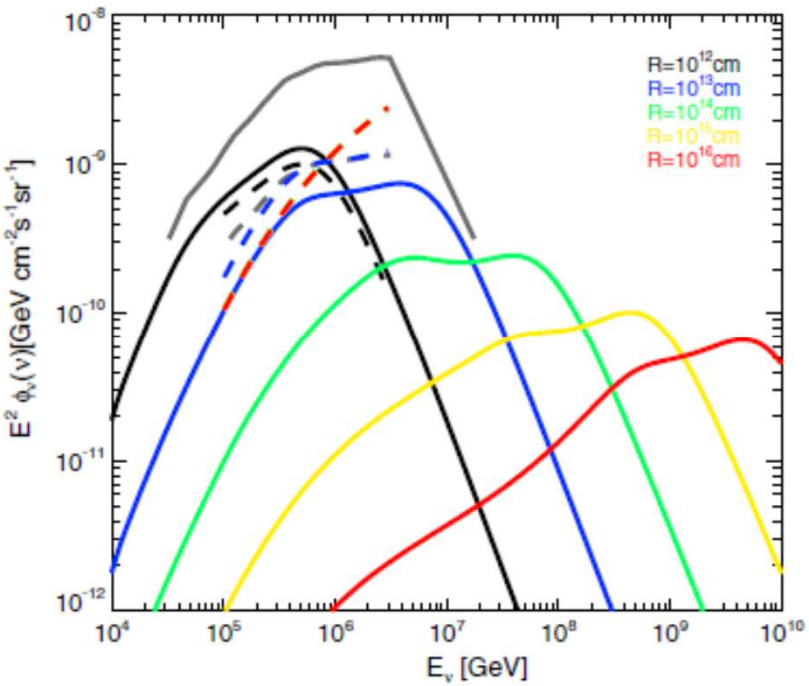
ICECUBE NONDETECTION OF GAMMA-RAY BURSTS: CONSTRAINTS ON THE FIREBALL PROPERTIES

Hao-Ning He[1,2,3], Ruo-Yu Liu[1,2], Xiang-Yu Wang[1,2], Shigehiro Nagataki[3], Kohta Murase[4], and Zi-Gao Dai[1,2]





PHYSICAL REVIEW D 85, 027301 (2012)

See also, Note on the normalization of predicted gamma-ray burst neutrino flux

Zhuo Li

Non detection of a very bright GRB

The Astrophysical Journal Letters, 772:L4 (5pp), 2013 July 20
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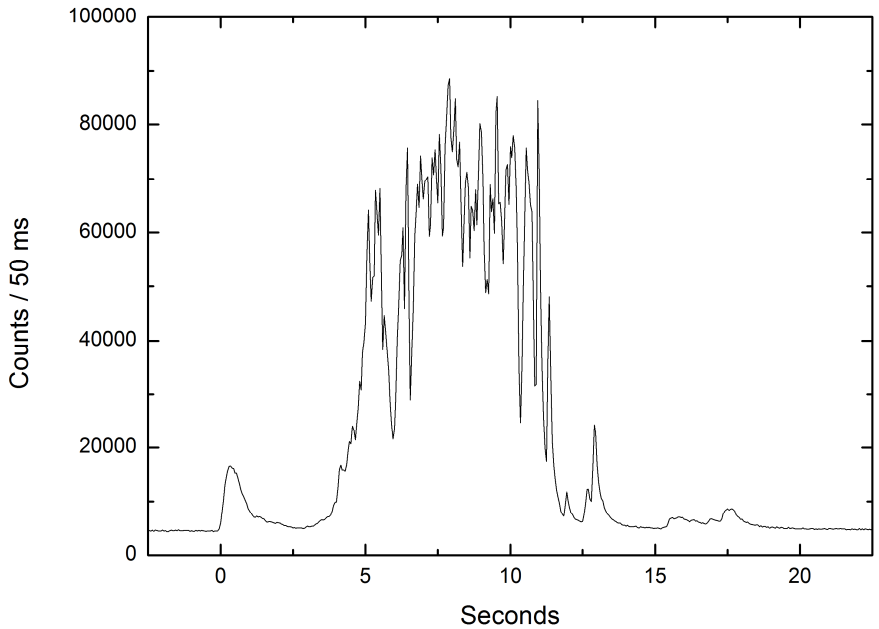
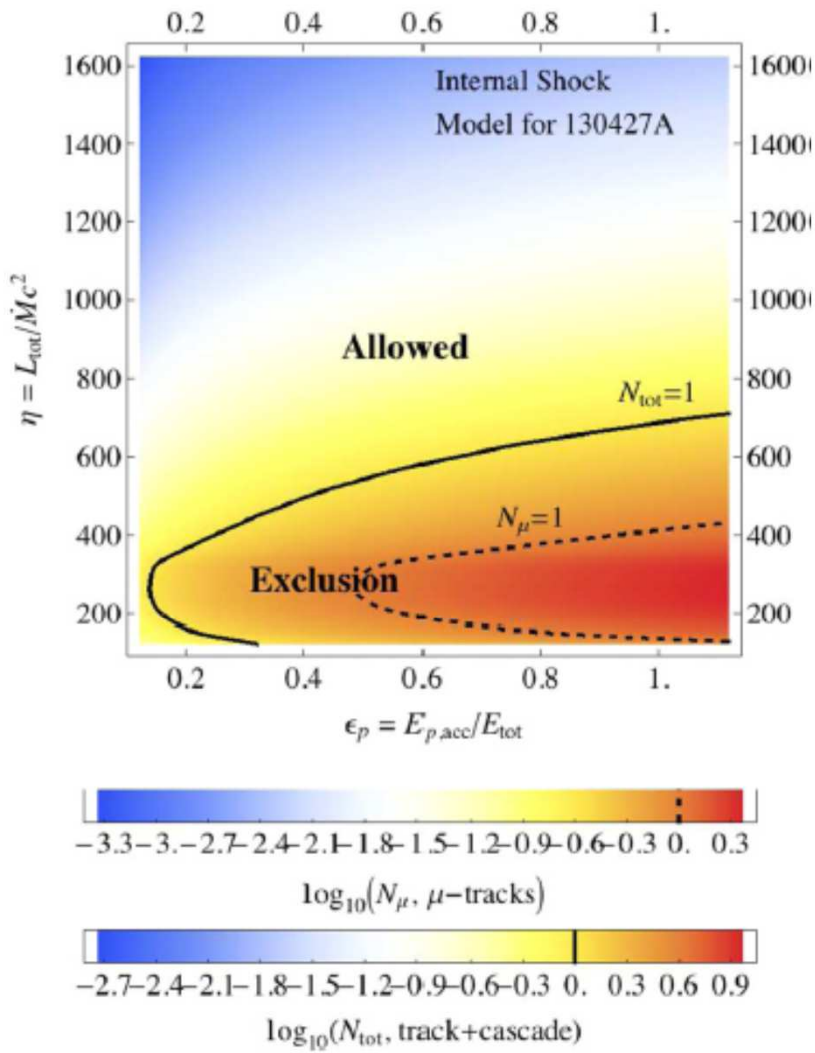
GRB 130427A



z=0.34
$\sim 10^{-3}$ erg/cm^2

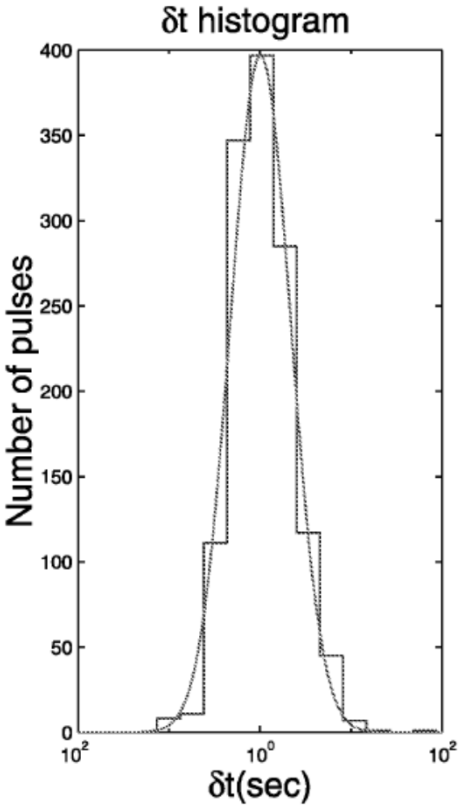
ON THE NEUTRINO NON-DETECTION OF GRB 130427A

Shan Gao, Kazumi Kashiyama, and Peter Mészáros

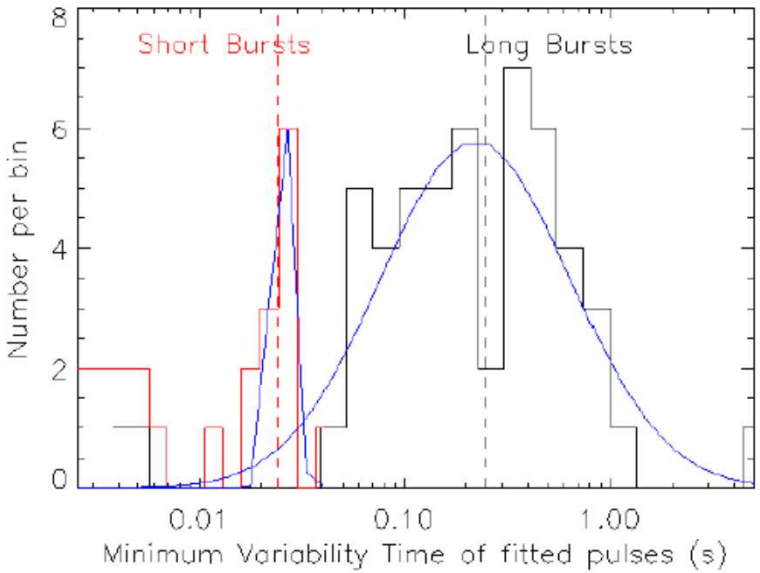


Revisiting the classical model

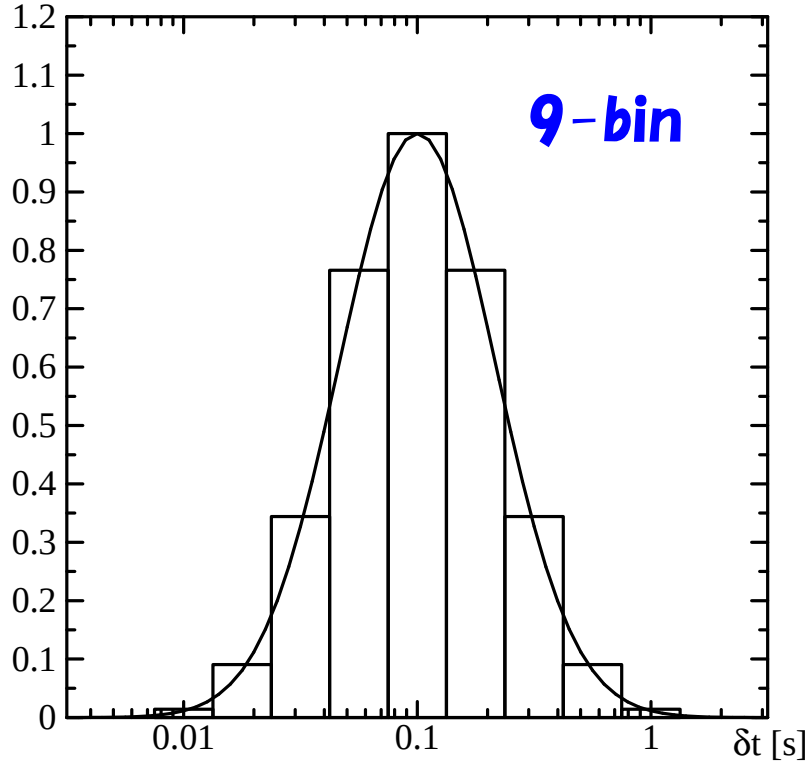
Pulse timescale



Nakar & Piran 2002
Log-normal: $\sigma = 0.77$



Bhat 2013

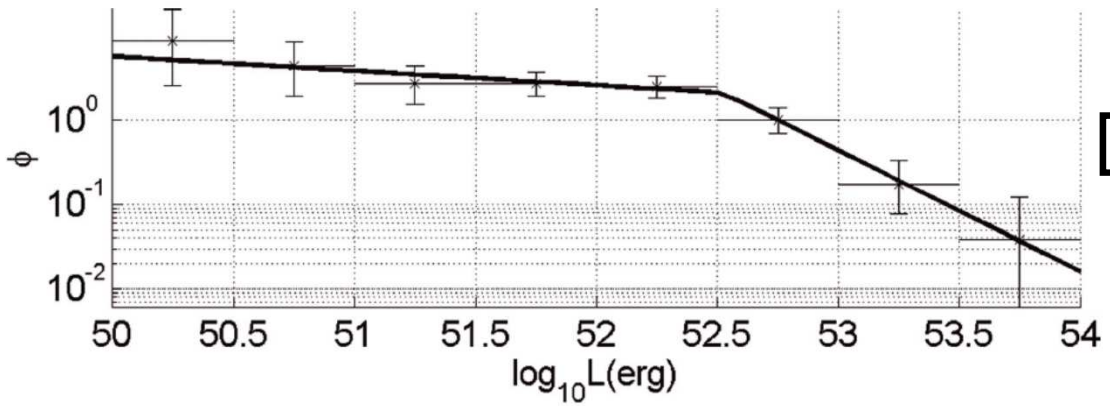


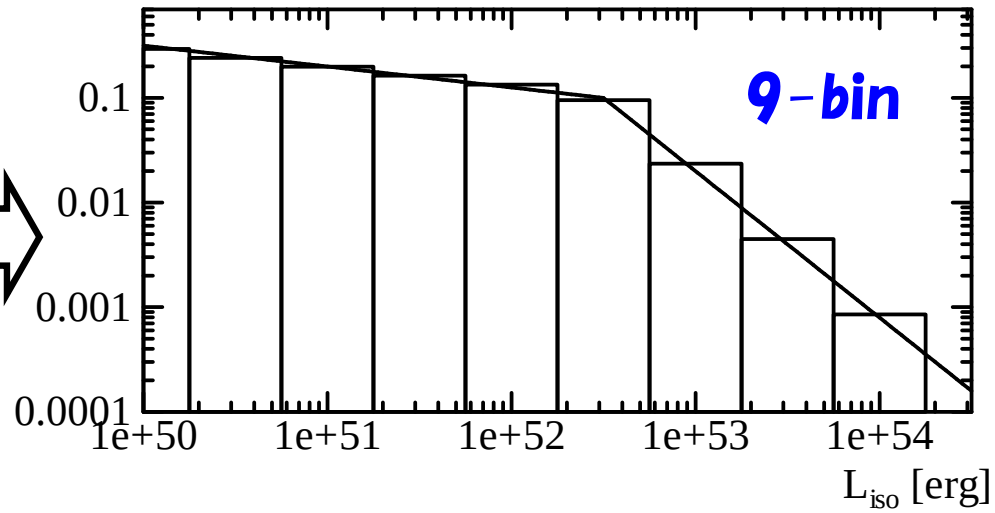
Emission radius

$$R \sim c\delta t\Gamma^2$$

Revisiting the classical model

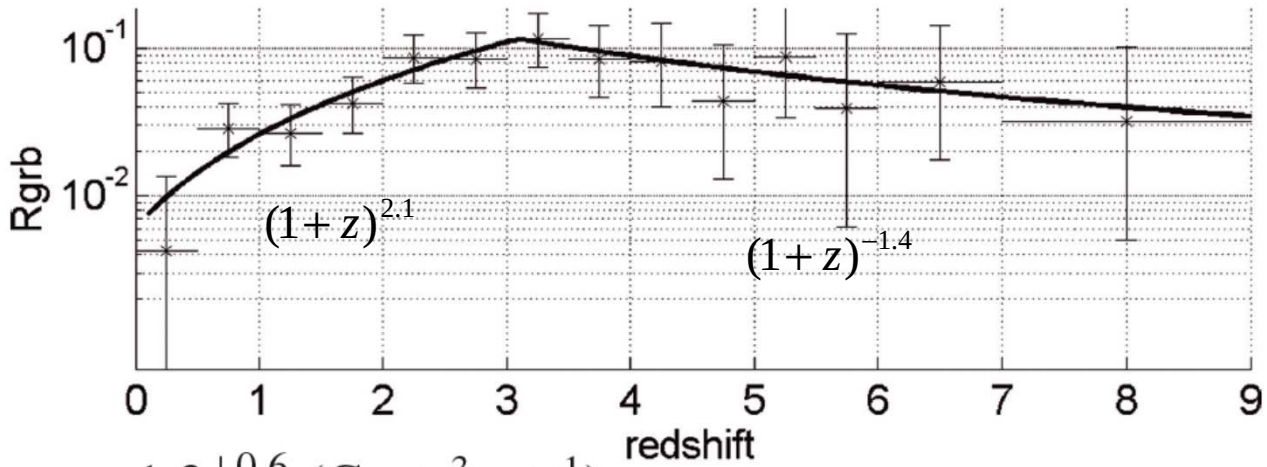
Luminosity function



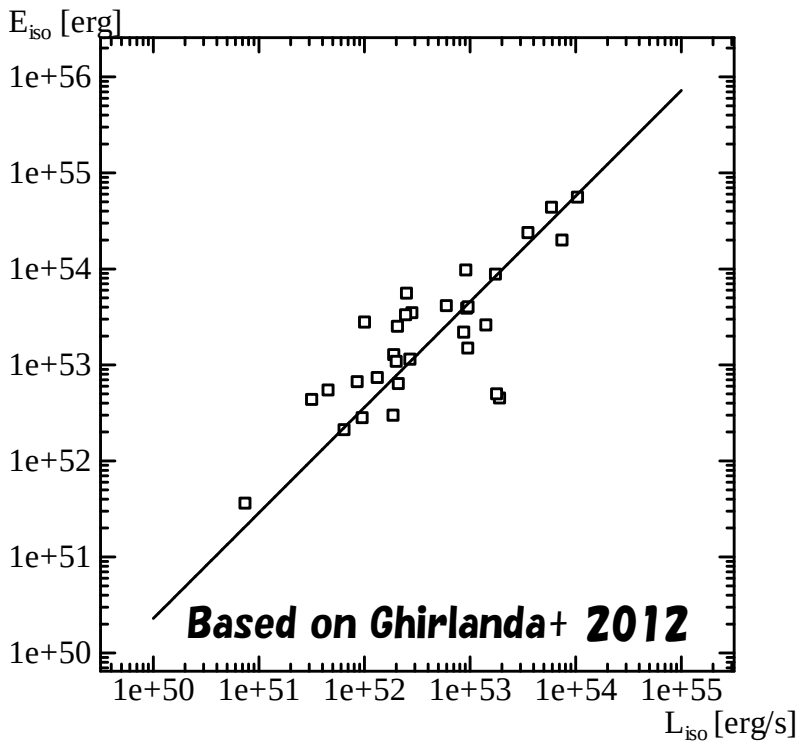


Wanderman & Piran 2010

Redshift distribution



$\rho_0 \simeq 1.3^{+0.6}_{-0.7}\ (\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1})$



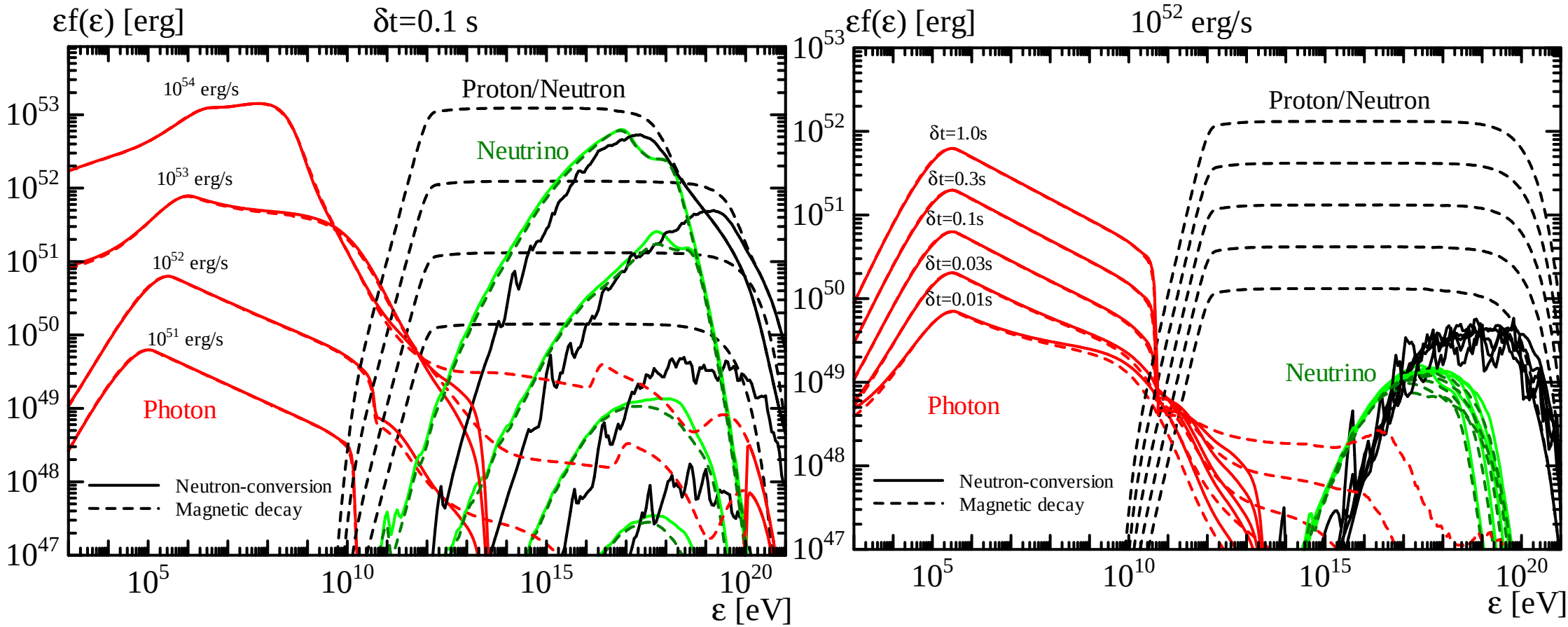
+ Yonetoku relation

Time-dependent simulation

$$\frac{L_p}{L_\gamma} = 10, \frac{L_B}{L_\gamma} = 0.1$$

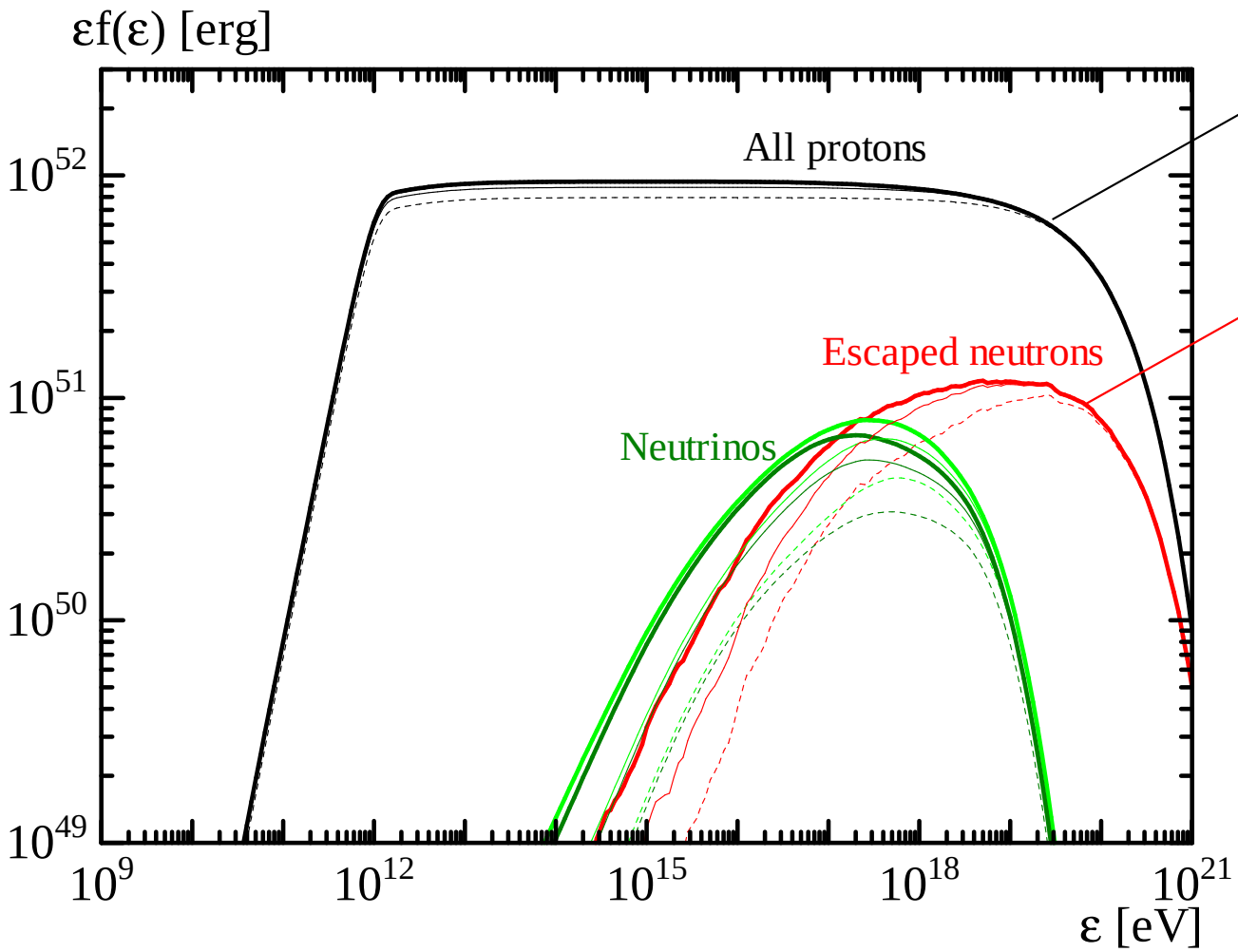
$$\Gamma = 300$$

Spectra from one pulse



Numerical code: Asano & Meszaros 2012

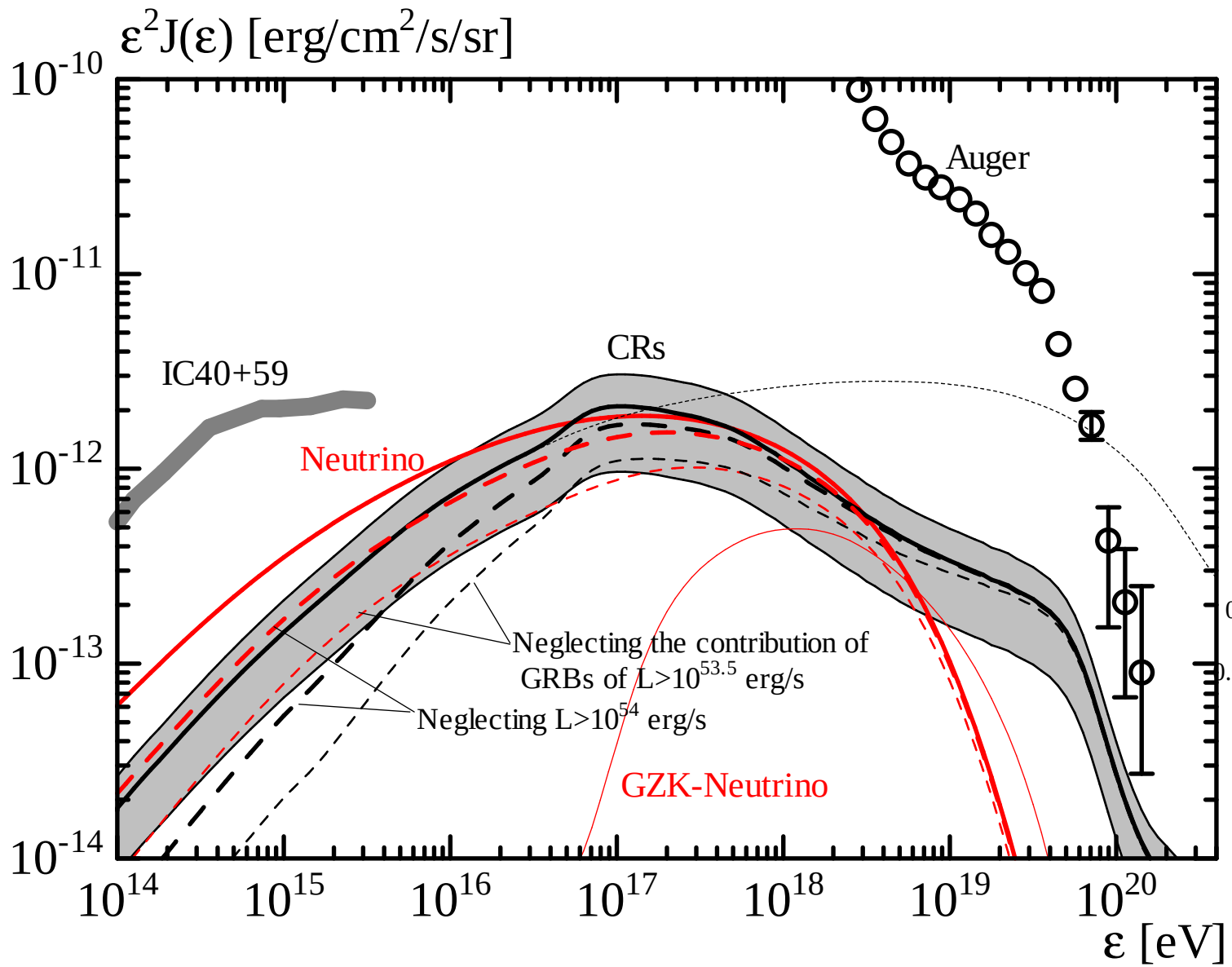
Average spectra from a GRB



Optimistic case for UHECR production.

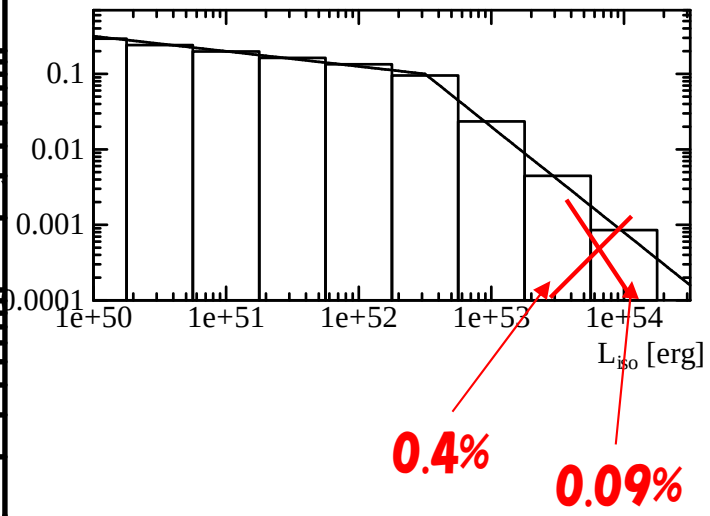
Pessimistic case

Neutron-conversion model



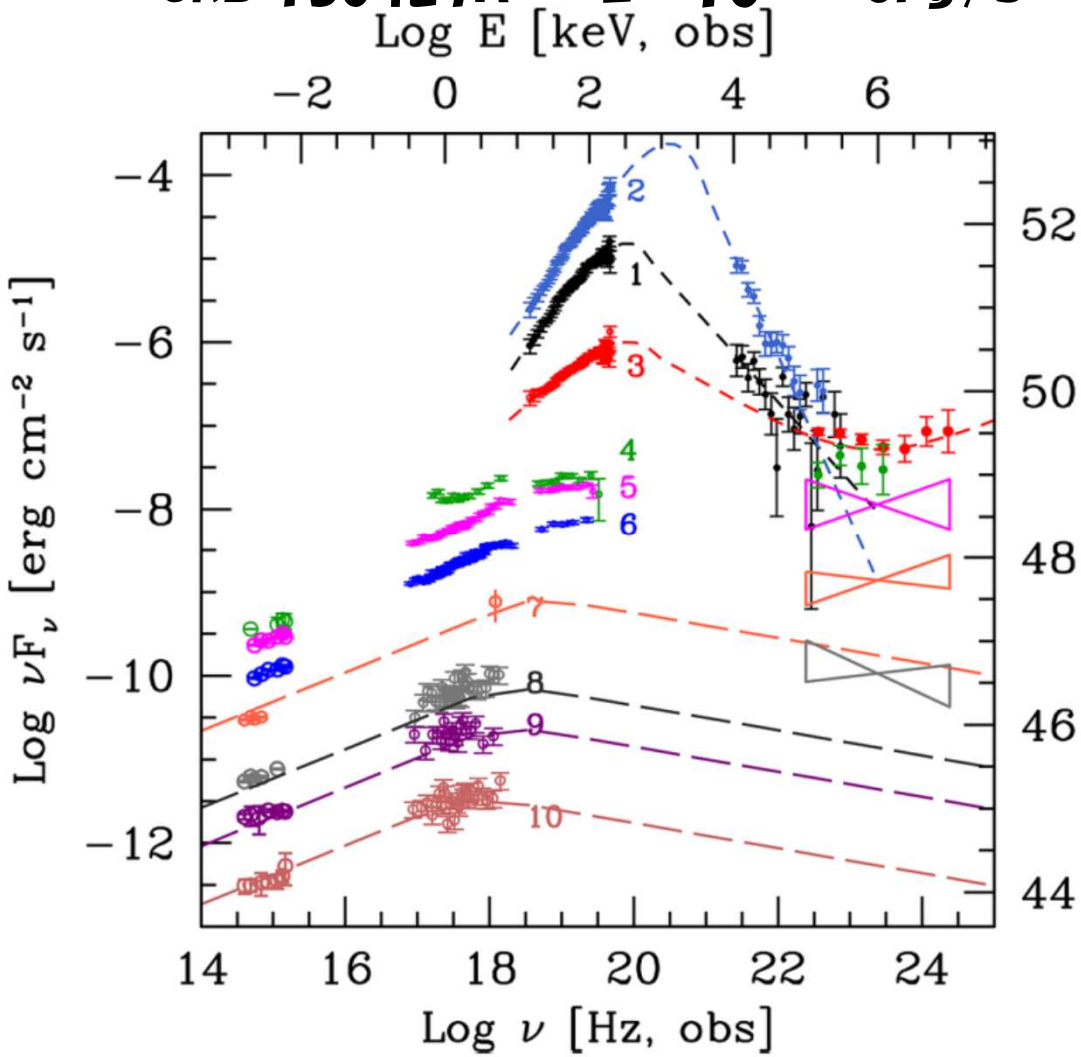
$$\frac{L_p}{L_\gamma} = 10, \frac{L_B}{L_\gamma} = 0.1$$

$$\Gamma = 300$$



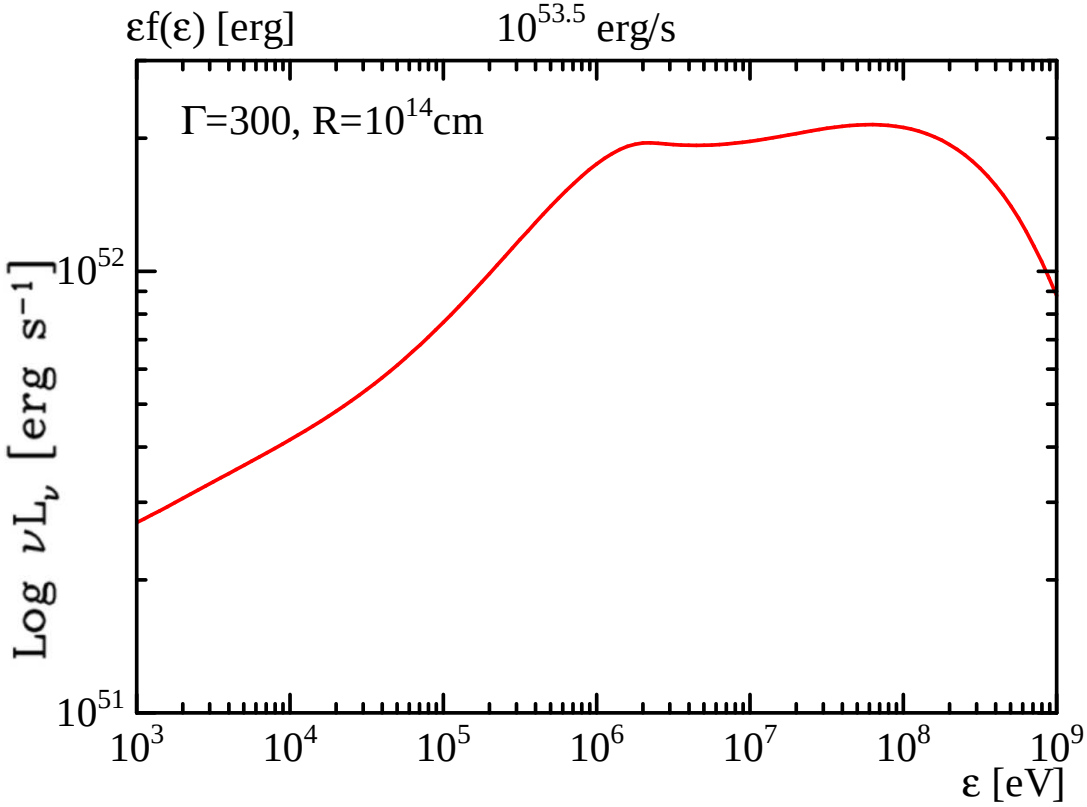
Bright GRBs are inconsistent with the benchmark

GRB 130427A $L \sim 10^{53.5}$ erg/s



Maselli+ 2013

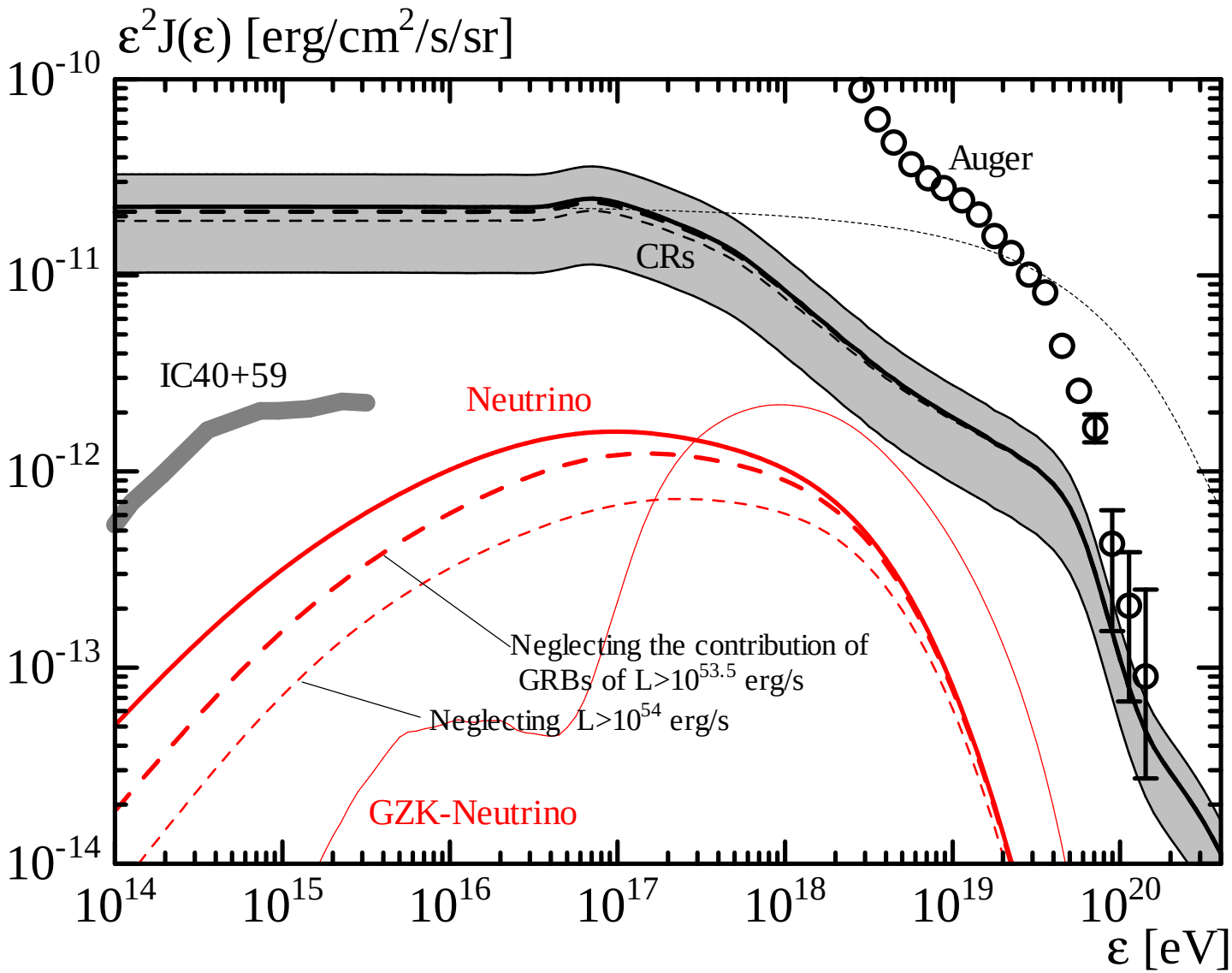
Model calculation



Cascade emission dominates!

→ High Γ, or low Lp

Optimistic model



UHECR escaping from $R=3R_0$

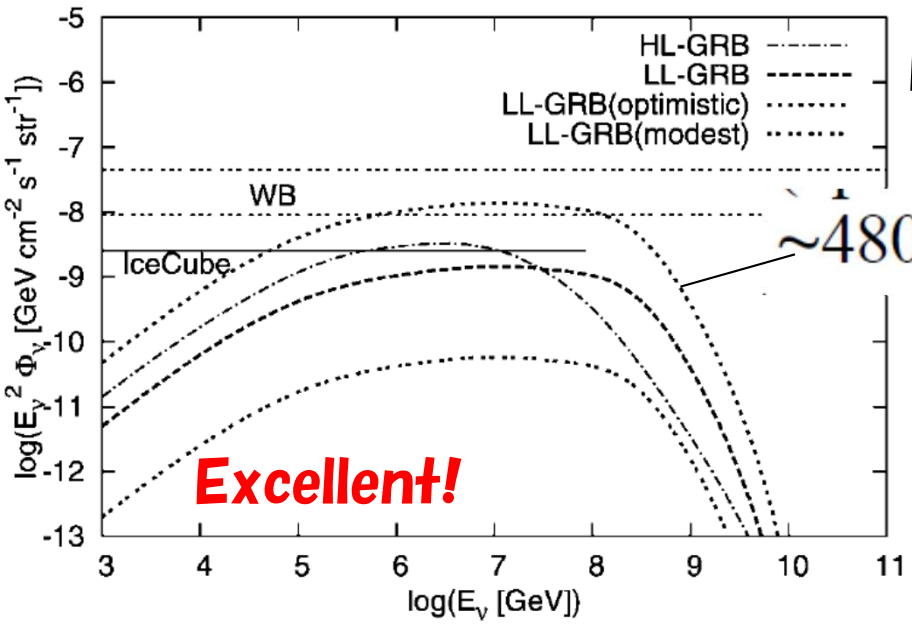
$$\frac{L_p}{L_\gamma}=10,\ \frac{L_B}{L_\gamma}=0.1$$

$$\Gamma=300$$

Summary

- We have many options: Internal/external, 1st/2nd-Fermi, Synchrotron/Thermal, baryonic/magnetic…
- IceCube constrained only neutrinos from a small fraction of GRBs (bright end)
- Highest energy UHECRs can be originated from GRBs, but 10^{19}eV CRs are…

Neutrinos from low-luminosity GRBs



Murase+ 2006

$\sim 4800\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$

We need to verify this. Photon signature of hadronic cascade in LL-GRB?

consistent with recent PeV detection