High Energy Neutrino Emission from Gamma-Ray Bursts

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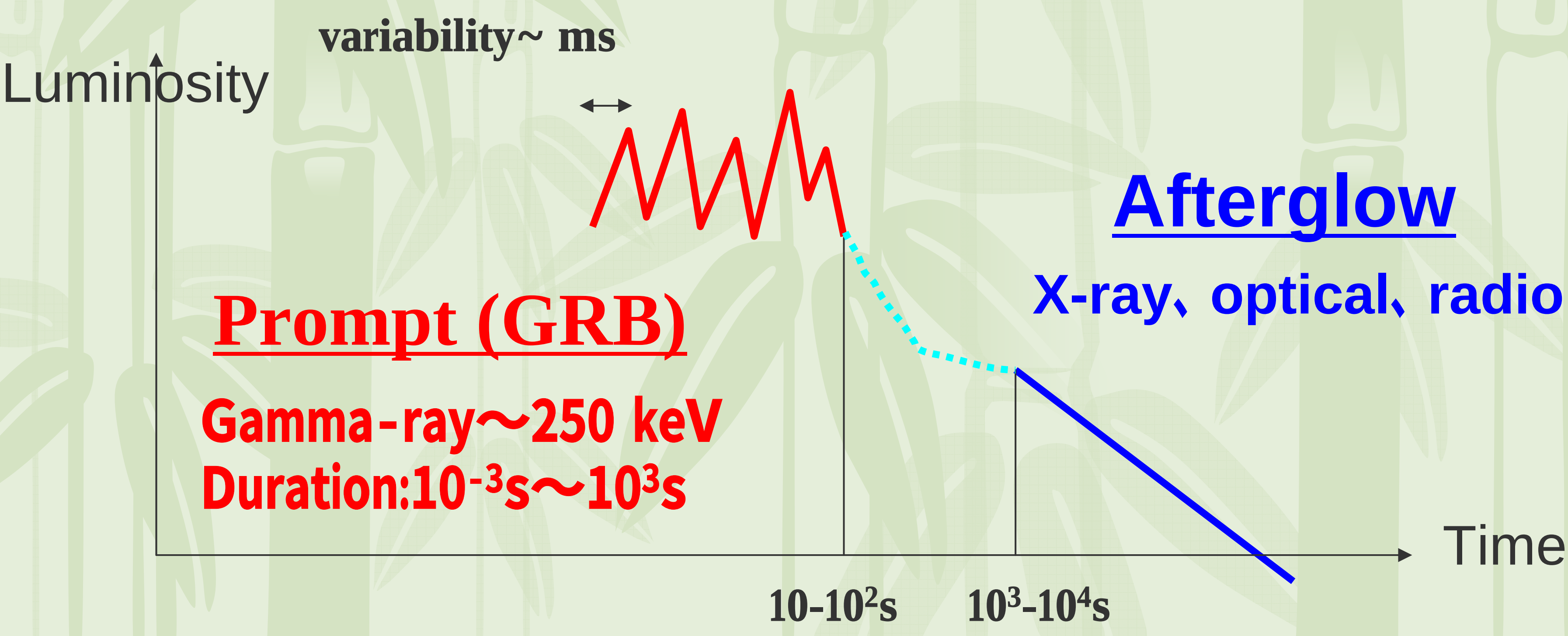
Gamma-Ray Bursts

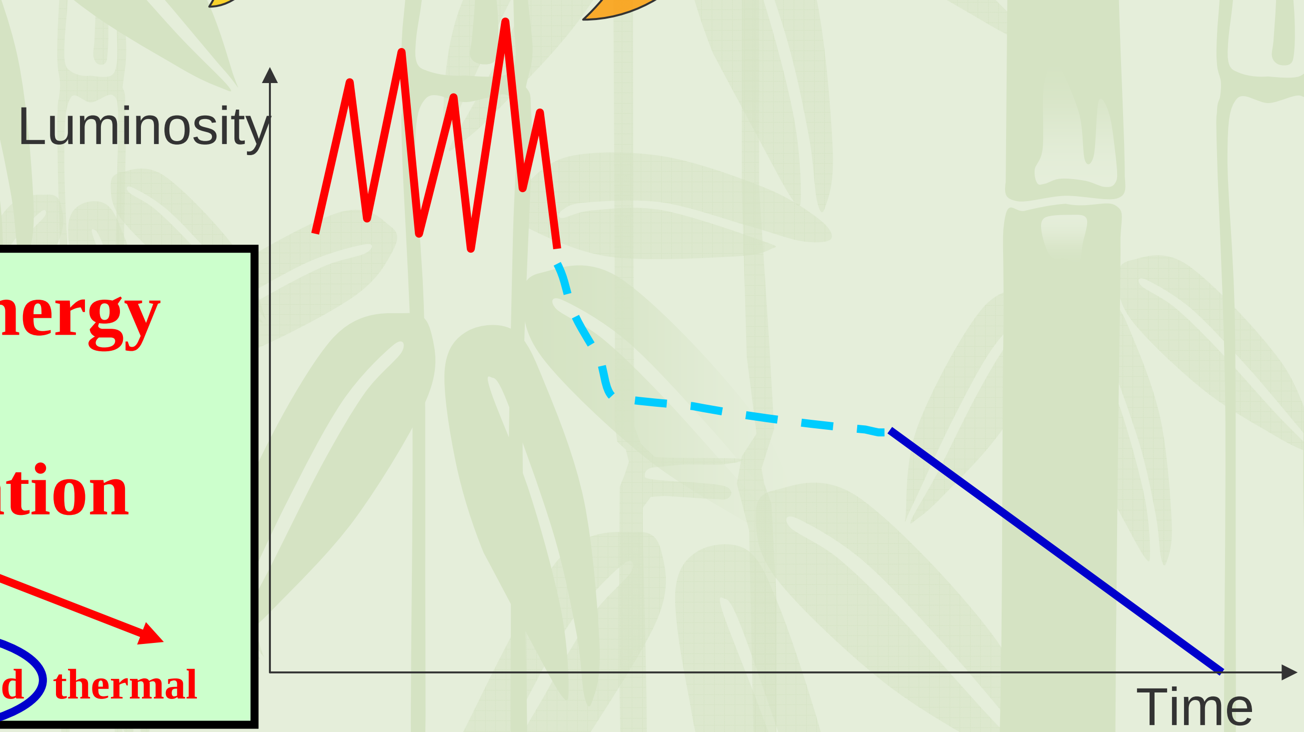
- **The most violent phenomena in the universe (L~$10^{51\text{-}52}$ ergs s^{-1})**
- **Cosmological events (z~1-3)**
- **The rate is ~1000 per year (~1/1000 of the SNe rate)**
- **Jet hypothesis (but the jet formation mechanism is unsolved)**
- **Related to the deaths of massive stars (SNe associations)**



Internal-External Shock Model

(See also talk by Dr. Guetta)

Γ>100



Bulk kinetic energy

↓

Shock dissipation

acceleration **magnetic field** **thermal**

Probing Proton Acceleration via Neutrinos

Internal-external shock model

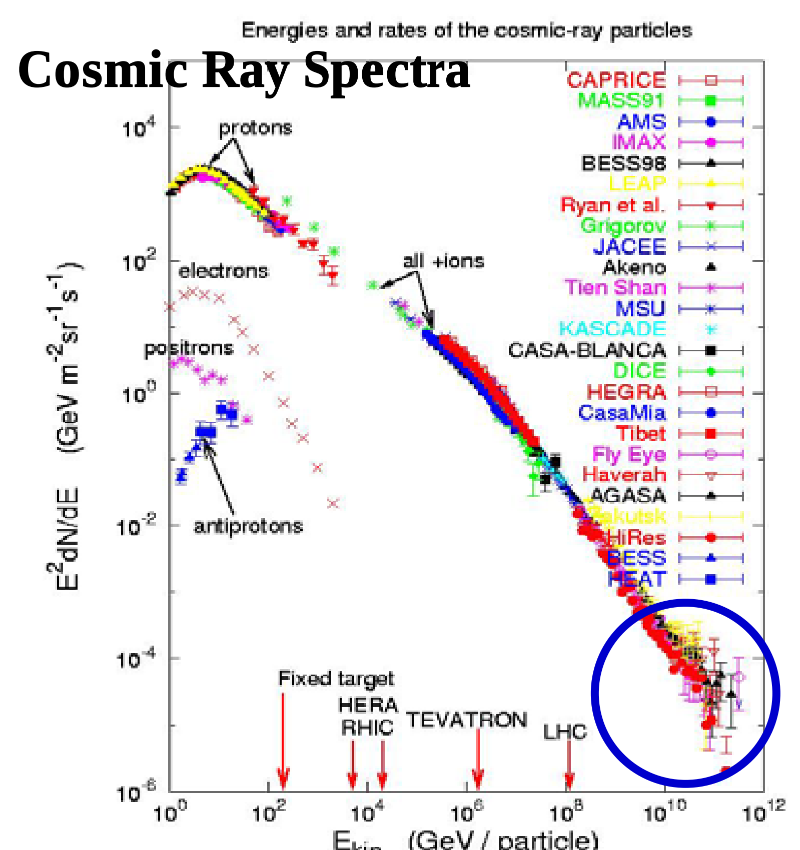
→ protons may be accelerated as well as electrons

p γ reaction $p + \gamma \rightarrow \pi, K \rightarrow \nu, \gamma$

In GRBs, neutrinos are the very evidence of proton acceleration

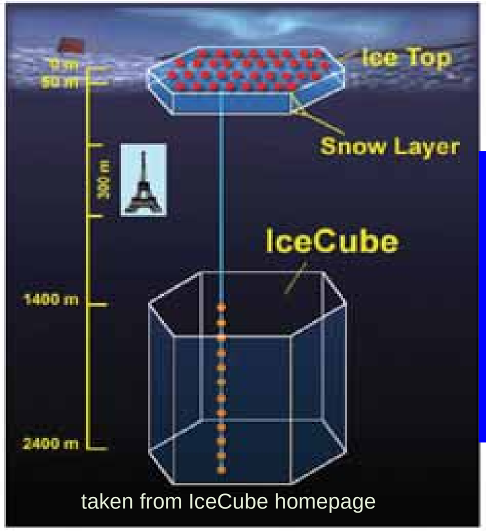
(∵Gamma-rays from π^0 decay should suffer from attenuation)

Cosmic Ray Spectra



- **Testing the shock model of GRBs**
- **Magnetic field / amount of baryons**
- **The origin of observed UHECRs?**

(Waxman 95) (Vietri 95)



Various model predictions have become testable by IceCube/KM3Net

What's New?

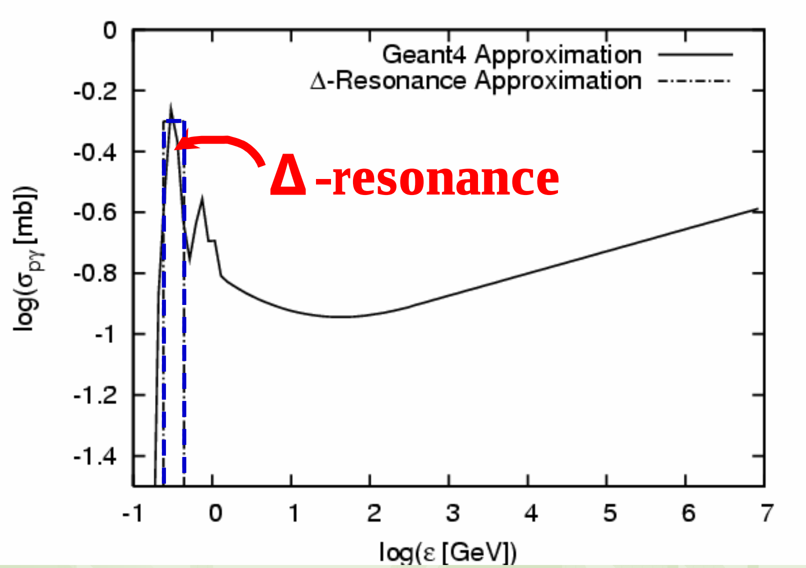
Prompt (Waxman & Bahcall 97), Afterglow (Waxman & Bahcall 00)

•Assumption that observed UHECRs come from GRBs
•Prediction of neutrinos associated with prompt and afterglow emission

(And many studies, e.g., Halzen & Hooper 99, Dermer 02, Guetta, Hooper, et al. 04)

•**Treatment for p γ reaction:**
Rectangular approx.→More sophistication
•**Treatment for the GRB rate history:**
GRB rate models→e.g. Guetta et al. (04,07)

KM & Nagataki, PRD, 73, 063002 (2006)



+

Motivated by the recent Swift's discoveries, we have predicted new possibilities of neutrinos and cosmic rays.

KM & Nagataki, PRL, 97, 051101 (2006) KM, Ioka, Nagataki, & Nakamura, ApJL, 651, L5 (2006)
KM, arXiv:0707.1140 (2007)

Method of Calculation

Proton distribution → Fermi-type spectrum

Photon distribution → given under the internal-external magnetic field shock model

p γ reaction

$$p+\gamma \rightarrow \Delta \rightarrow n+\pi^{+} \quad \kappa_p \sim 0.2$$ **Δ**-resonance

$$p+\gamma \rightarrow N\pi^{\pm}+X \quad \kappa_p \sim (0.4-0.7)$$ multi-pion production

Experimental data + Geant4

Cross Section + Multiplicity + Inelasticity

Pions and muons decay to neutrinos

$$\pi^{\pm} \rightarrow \mu^{\pm}+\nu_\mu(\bar{\nu}_\mu) \rightarrow e^{\pm}+\nu_e(\bar{\nu}_e)+\nu_\mu+\bar{\nu}_\mu$$

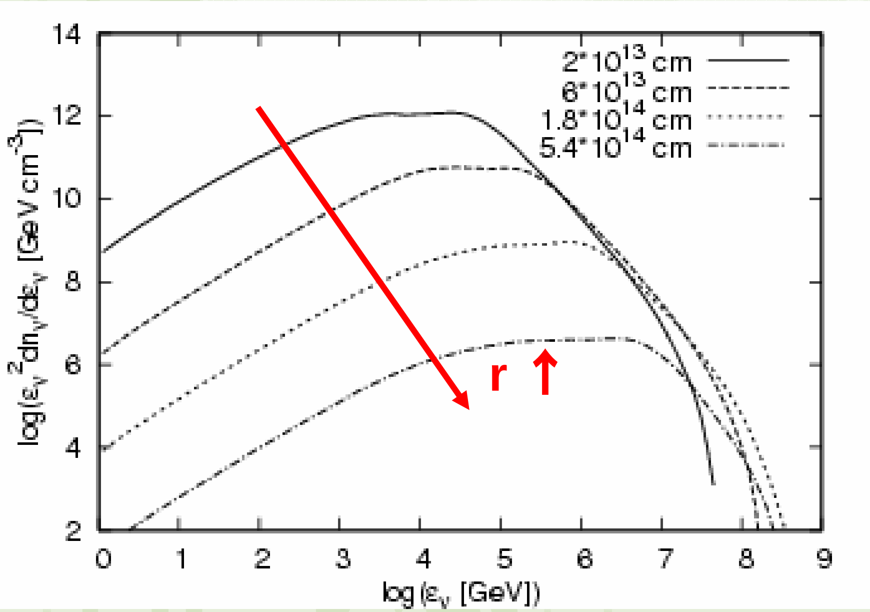
Cooling processes

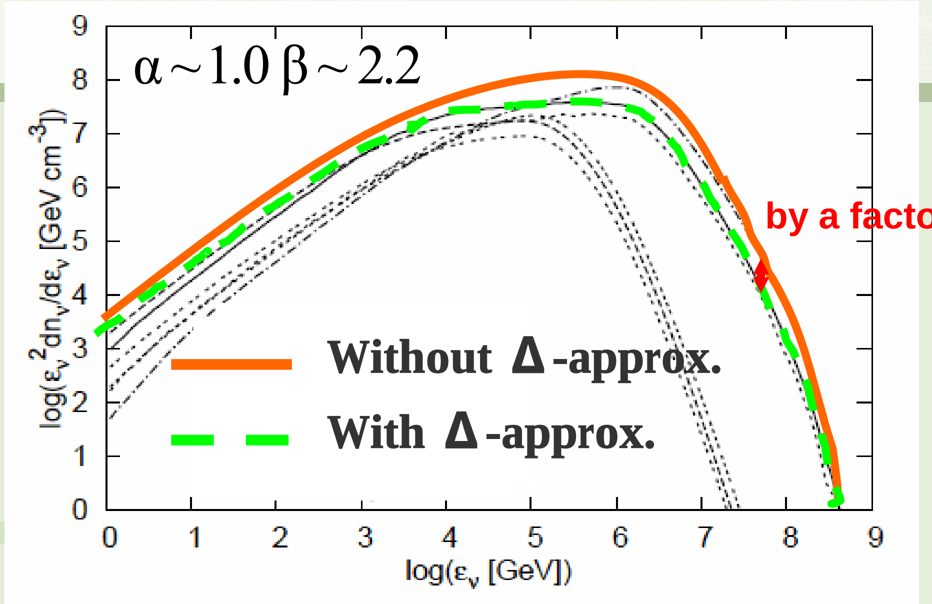
- **Synchrotron cooling**
- **Adiabatic cooling**
- **Inverse Compton cooling**

Calculating neutrinos flux assuming the GRB rate history (Results are not so sensitive to GRB rate models)

TeV-PeV Neutrinos from Internal Shocks

KM & Nagataki, PRD, 73, 063002 (2006)





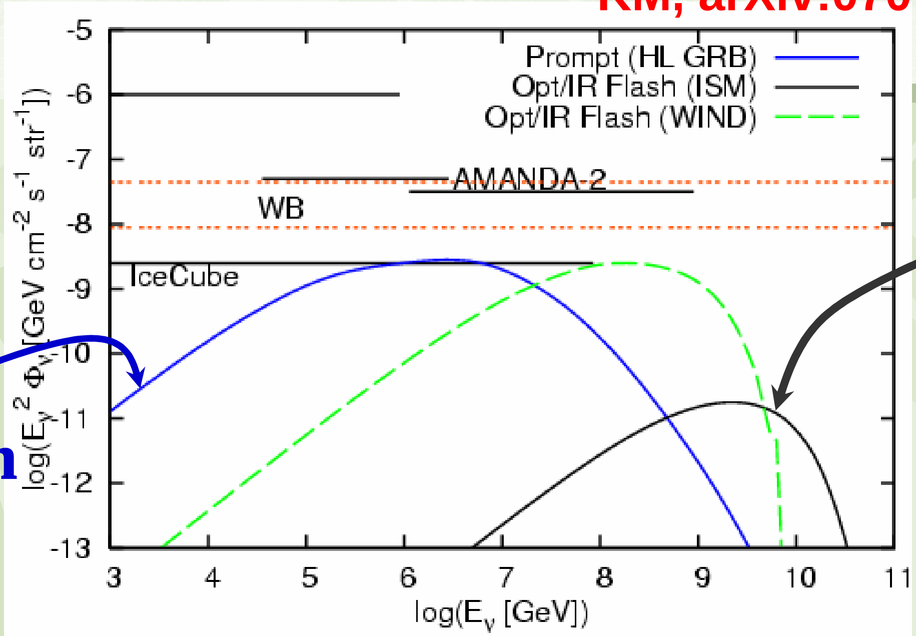
•At radii <~ 10^{14} cm, photomeson production efficiency can be high, $f_{p\gamma}$ ~1, where almost accelerated protons will be depleted.
•At larger radii, UHECRs could be produced and ν's energy can be higher (Asano 05).

•p γ cross section in high energies (above Δ-resonance) is moderately important, which can enhance neutrino fluxes by a factor.

• **Uncertainties and possible fluctuations of collision radii r and Lorentz factor Γ (e.g., Halzen & Hooper 99) → More comprehensive observations/studies**
• **Neutrinos from an energetic/nearby GRB event only can be detected by IceCube (e.g., Dermer & Atoyan 03). → We have to see many GRB events.**

Neutrino Predictions in the Pre-Swift Era

KM & Nagataki, PRD, 73, 063002 (2006)
KM, arXiv:0707.1140 (2007)



Prompt Emission

Opt/IR flash (reverse shock)

For forward shock νs, see, e.g., Dermer 02.

(The baryon energy in highest energies E_{HECR})~(GRB prompt radiation energy E_{GRB})

- **ν bursts→Coincidence with bursts, ~10 events/yr (IceCube)**
- **ν afterglows→Coincidence with afterglows, < 1 events/yr (IceCube)**

(However, recent observations have suggested the lack of optical/IR flashes…)

More detailed calculation of ν spectra (→similar to WB flux, but increase by a factor)

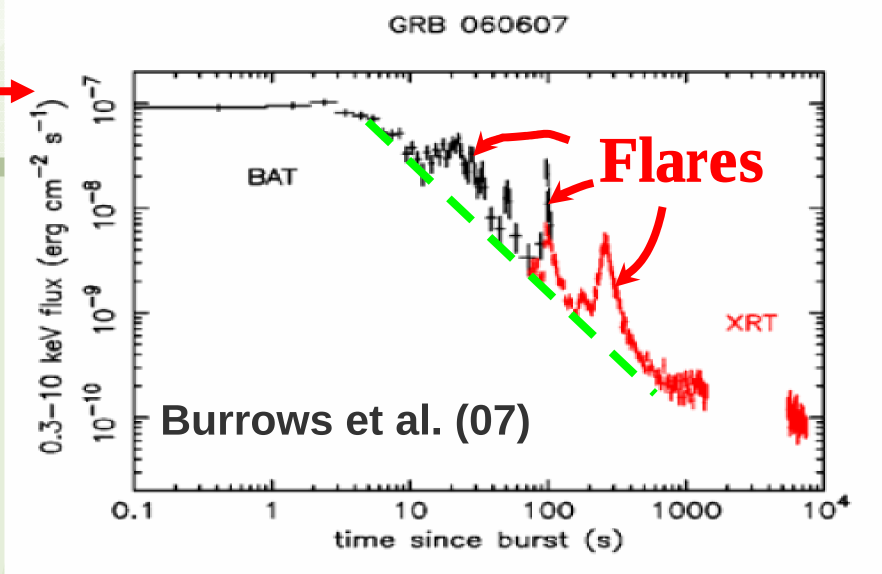
Our result (E_{HECR} ~ 10 E_{GRB}) has been constrained. (→next talk by Dr. Taboada)

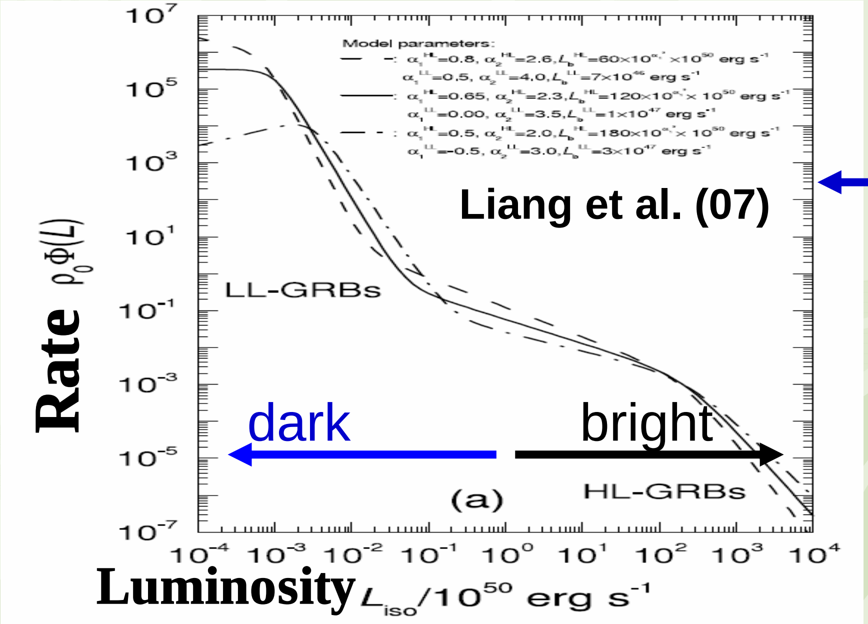
However, there are other possibilities of neutrino signals…

The Discoveries by Swift Satellite

①Flares in the early afterglow

- Typically $E_{flare} \sim 0.1\ E_{GRB}$ (Falcone et al. 07)
  Some flares $E_{flare} \sim E_{GRB}$ (Falcone et al. 05)
- Flaring in the far-UV/x-ray range
- Relatively lower Lorentz factor
- Baryonic model vs non-baryonic one





②Low-luminosity (LL) GRBs

- GRB060218 is the second nearby event associated with a SN Ic.
- It is much dimmer than usual GRBs.
  $E_{LL} \sim 10^{50}$ ergs $\sim 0.001\ E_{GRB}$
  (we couldn't see if it occurred at >~200Mpc.)
- LL GRBs will be more frequent.

If baryon acceleration occurs in flares and/or LL GRBs, how much contribution to neutrinos/CRs can we expect?

The Contributions from Flares and LL GRBs

Neutrino Energy Flux $\propto$ Rate $\times$ Photopion ($p \rightarrow \pi$) Production Efficiency $\times$ Nonthermal Baryon energy

↓ Normalizing all the typical values for HL GRBs to 1

	HL GRB (Waxman & Bahcall 97)	Flare (Murase & Nagataki 06)	LL GRB (Murase et al. 06) (Gupta & Zhang 07)
Isotropic energy	1	~0.01-0.1	0.001
Pion Production Efficiency	1	10	1
Rate	1	1	~100-1000
The contribution to neutrino background	1	~0.1-1	~0.1-1

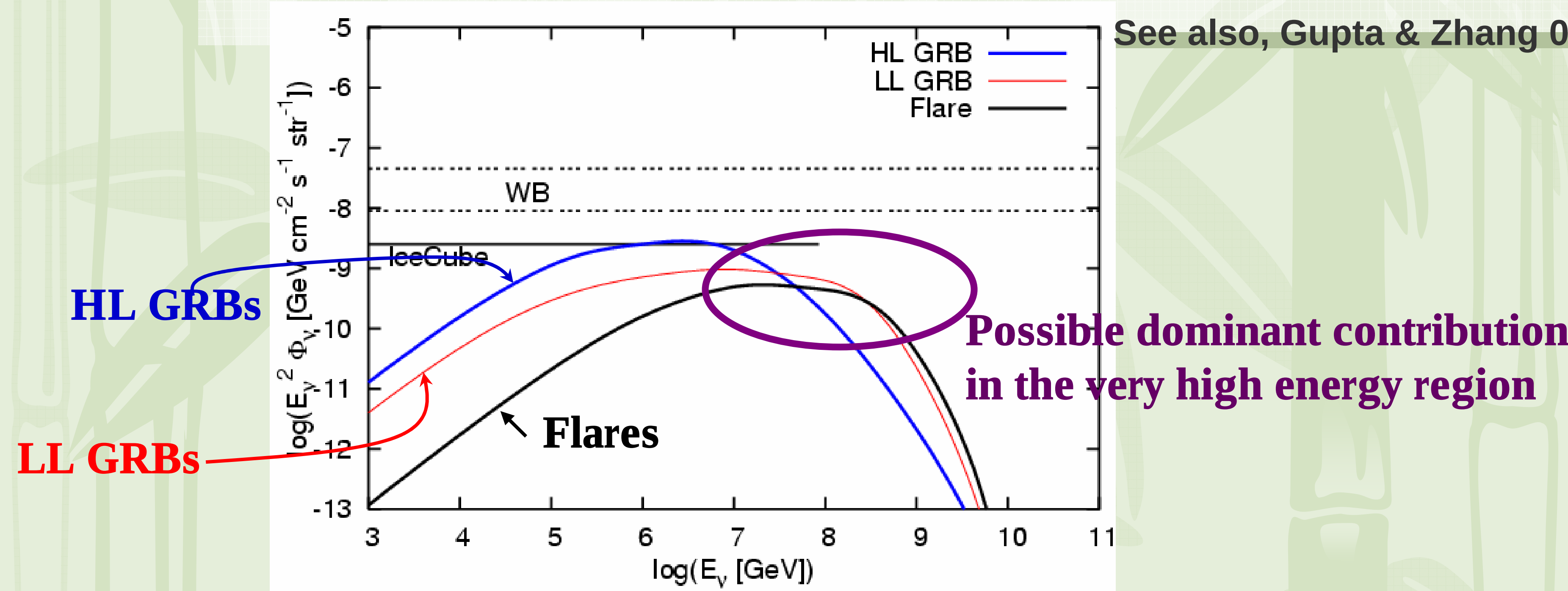
Hence, we can expect flares and LL GRBs are important!

Neutrino Predictions in the Swift Era

KM & Nagataki, PRL, 97, 051101 (2006)

KM, Ioka, Nagataki, & Nakamura, ApJL, 651, L5 (2006)

See also, Gupta & Zhang 07



ν flares → Coincidence with flares / early afterglows, a few events / yr

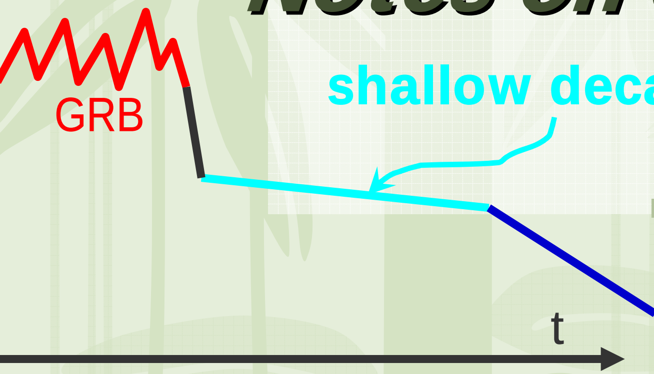
ν s from LL GRBs → little coincidence with bursts, a few events / yr

Approaches to GRBs through high energy neutrinos

Flares→information on flare models (baryonic or nonbaryonic etc.)

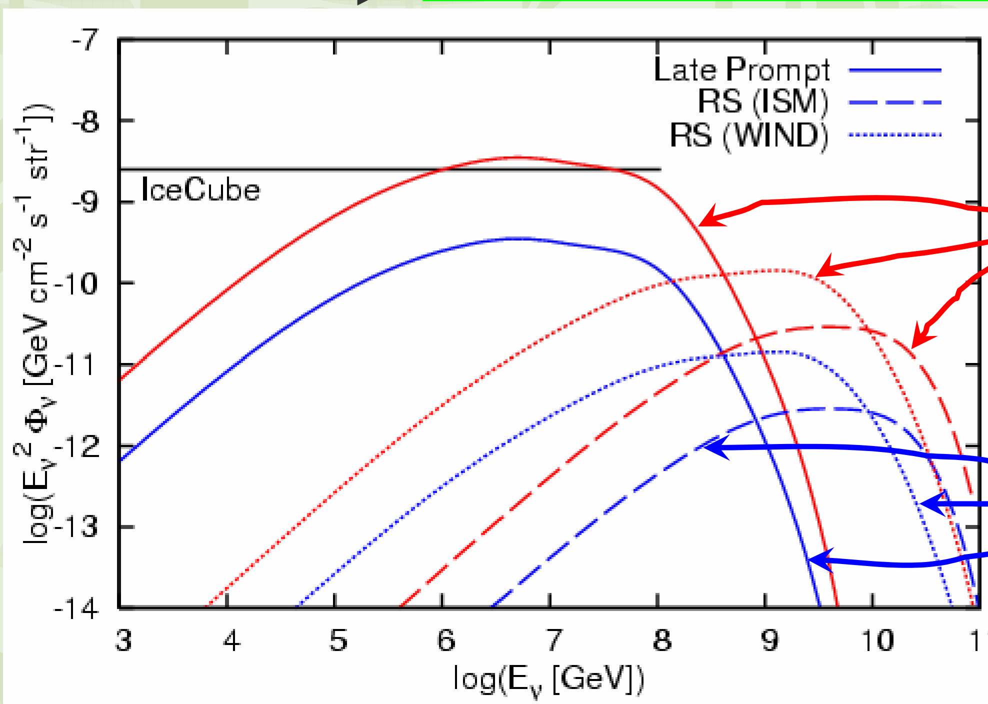
LL GRBs→ν s as an indicator of far SNe associated with LL GRBs

Notes on Shallow Decay Emission



Its origin is still controversial...

- **Forward Shock Model (energy injection etc.)**
- **Reverse Shock Model** (Genet et al. 07, Beloborodov 07)
- **Late Prompt Emission Model** (Ghisellini et al. 07)



KM, arXiv:0707.1140 (2007)

higher baryon loading
$E_{HECR} \sim E_{GRB}$

moderate baryon loading
$E_{HECR} \sim E_{shallow}$
$\sim 0.1\ E_{GRB}$

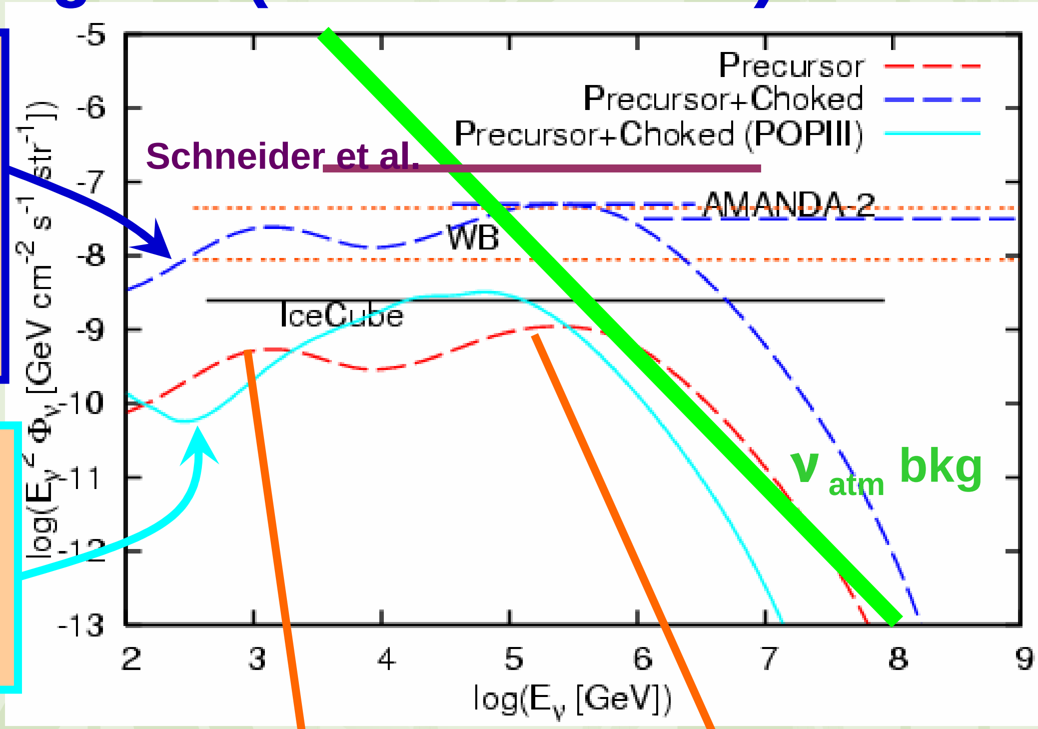
- **Typically $E_{shallow} \sim 0.1\ E_{GRB}$ (Liang et al. 07) → It will be difficult to detect neutrinos by IceCube, especially in the external shock model.**
- **In the late prompt emission model, neutrinos could be detected.**

Notes on Neutrinos from inside a Progenitor

Internal shocks and a termination shock inside a star may lead to baryon acceleration. (Meszaros & Waxman 01, Razzaque et al. 03, Ando & Beacom 05)

→ **precursor neutrinos signals (for successful GRBs)**
or **choked neutrino signals (for failed GRBs)**

•Possible choked signals?
•choked ν s → diffuse background
•The AMANDAII limit implies (# of failed GRBs)/(# of SNe-Ibc) <~ 0.5 with $\mathbf{E_{HECR} \sim E_{GRB} \sim 10^{53}}$ **ergs**



•Possible POPIII contribution?
•Schneider et al. (02) → overestimation
• ν detection would be difficult, even if all the POPIIIs can produce GRBs.

But, there are large uncertainties in the model.

Iocco, KM, et al., arXiv:0707.0515 (2007)

ν s from jet head
(interaction between ps from IS and γ s from TS)

ν s from jets
(interaction between ps from IS and γ s from IS)

Neutrinos from GRBs: Summary

- We have performed more sophisticated calculations on neutrino spectra under the internal or external model.

  →Our results have been tested by AMANDA/IceCube.
- We have predicted new possibilities of neutrino emission from GRBs, motivated by Swift observations.

  1. Neutrinos from flares and early afterglows
  2. Neutrino bursts from low luminosity (LL) GRBs

- Neutrinos are useful as a probe of proton acceleration in GRBs. (for γ-rays, please see, e.g., Dermer et al. 07 and Asano & Inoue 07)
- If detected, we can obtain the important clues to models of GRBs and/or baryon acceleration.
- The connection between GRBs and UHECRs?

  (e.g., Anchordoqui, Hooper, et al. 07)
- Neutrino physics (for oscillation, e.g., Kashti & Waxman 05)
- High energy neutrino astronomy will come soon!

End

Grazie!

Acknowledgements:

- This presentation is supported by the Grant-in-Aid for the 21st Century COE "Center for Diversity and Universality in Physics" from the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan.
- Thanks for LOC.

Spares

UHECRs from GRBs

r_L < size

$t_{acc} < t_{dyn}$ + $t_{acc} < t_{cool}$

The criterions for determination of the maximum energy

①HL GRB & LL GRB → Synchrotron loss is important

$t_{cool} \sim t_{syn}$

HL GRB

$$0.14\eta(\Gamma/300)E_{p,20} \lesssim L_{M,51}^{1/2}\epsilon_B^{1/2}\left(\frac{\Gamma_{sh}(\Gamma_{sh}-1)}{2}\right)^{1/2} \lesssim 15\eta^{-1}r_{14}(\Gamma/300)^3E_{p,20}^{-2}$$

$$E_{max} = 7.3\times10^{20}\,\mathrm{eV}\,\eta^{-1}\epsilon_B^{1/2}\epsilon_e^{-1/2}\left[\frac{\Gamma_{sh}(\Gamma_{sh}-1)}{2}\right]^{1/2}L_{\gamma,51}^{1/2}\left(\frac{\Gamma}{300}\right)^{-1}$$

or

$$E_{max} = 3.9\times10^{20}\,\mathrm{eV}\,\eta^{-1/2}\epsilon_B^{-1/4}\epsilon_e^{1/4}\left[\frac{\Gamma_{sh}(\Gamma_{sh}-1)}{2}\right]^{-1/4}L_{\gamma,51}^{-1/4}\left(\frac{\Gamma}{300}\right)^{3/2}r_{14}^{1/2}$$

(Nonthermal baryon energy in the highest energies)～(GRB's radiation energy)

$\dot{E}_{UHECR} \sim 3\times10^{53}\,\mathrm{ergs\,yr^{-1}\,Gpc^{-3}}$ $(10^{18.5}-10^{20.5}\,\mathrm{eV})$ $\dot{E}_{\gamma} \sim 10^{53}\,\mathrm{ergs\,yr^{-1}\,Gpc^{-3}}$

LL GRBs→ Acceleration up to UHE region needs fine tuning

$$0.5\eta(\Gamma/10)E_{p,20} \lesssim L_{\mathrm{M},48}^{1/2}\epsilon_{B,-1}^{1/2}\left(\frac{\Gamma_{\mathrm{sh}}(\Gamma_{\mathrm{sh}}-1)}{2}\right)^{1/2} \lesssim 0.55\eta^{-1}r_{15}(\Gamma/10)^3E_{p,20}^{-2}$$

Energy budget can be sufficient for explanation of UHECRs

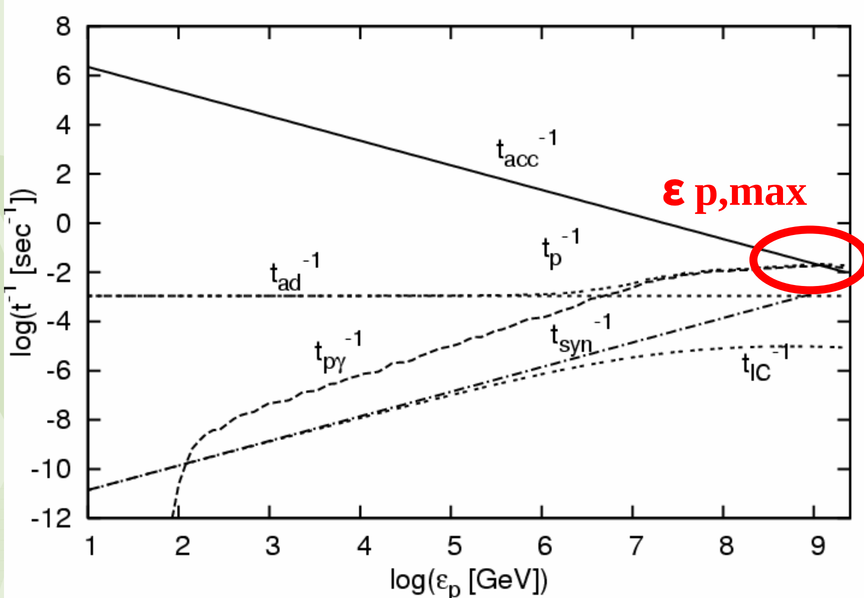
$$E_p^2\frac{d\dot{N}_p}{dE_p^2} \sim 2.5 \times 10^{43}\,\mathrm{ergs\,Mpc^{-3}\,yr^{-1}}\left(\frac{\xi_{\mathrm{acc}}}{10}\right) NL_{\mathrm{max},47}r_{15}\left(\frac{\Gamma}{10}\right)^{-2}\left(\frac{\rho_{\mathrm{LL}}(0)}{500\,\mathrm{Gpc^{-3}\,yr^{-1}}}\right)$$

②Flares → p γ loss is important

$t_{cool} \sim t_{p\gamma}$

$E_{max} \sim \Gamma\ \varepsilon_{max} \sim 10^{19}$ eV

Acceleration up to UHE energies is implausible



Photopion Production Efficiency

High luminosity (HL) GRBs

$$f_{p\gamma} \simeq 0.1 \frac{L_{\max,51}}{r_{14}(\Gamma/300)^2 E^{\rm b}_{300\,\rm keV}} \begin{cases} (E_p/E_p^{\rm b})^{\beta-1} & (E_p < E_p^{\rm b}) \\ (E_p/E_p^{\rm b})^{\alpha-1} & (E_p^{\rm b} < E_p) \end{cases}$$

Low luminosity (LL) GRBs

$$f_{p\gamma} \simeq 0.06 \frac{L_{\max,47}}{r_{15}(\Gamma/10)^2 E^{\rm b}_{5\,\rm keV}} \begin{cases} (E_p/E_p^{\rm b})^{\beta-1} & (E_p < E_p^{\rm b}) \\ (E_p/E_p^{\rm b})^{\alpha-1} & (E_p^{\rm b} < E_p) \end{cases}$$

Far-UV/x-ray flares

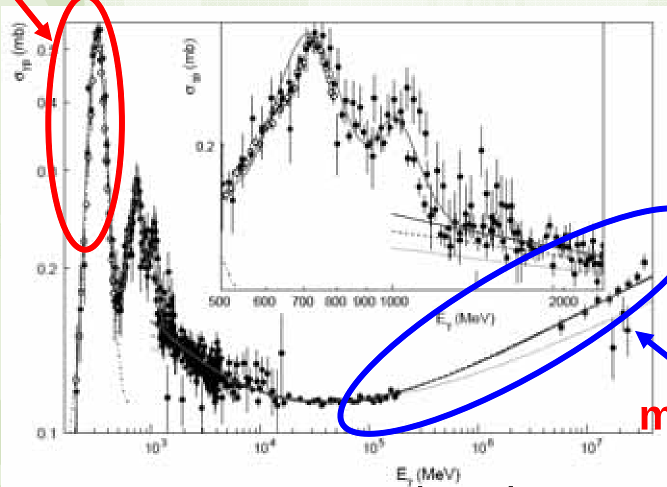
$$f_{p\gamma} \simeq 6 \frac{L_{\max,48.5}}{r_{15.5}(\Gamma/10)^2 E^{b}_{0.5\,\rm keV}} \begin{cases} (E_p/E_p^{b})^{\beta-1} & (E_p < E_p^{b}) \\ (E_p/E_p^{b})^{\alpha-1} & (E_p^{b} < E_p) \end{cases}$$

Photomeson Production

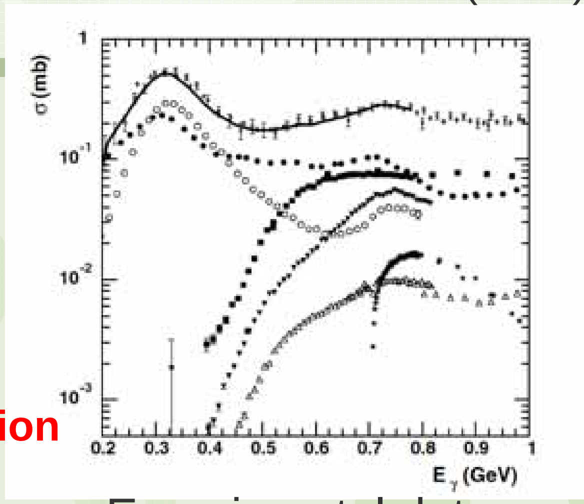
Δ -resonance

Kossov (2002)

Schadmand (2003)

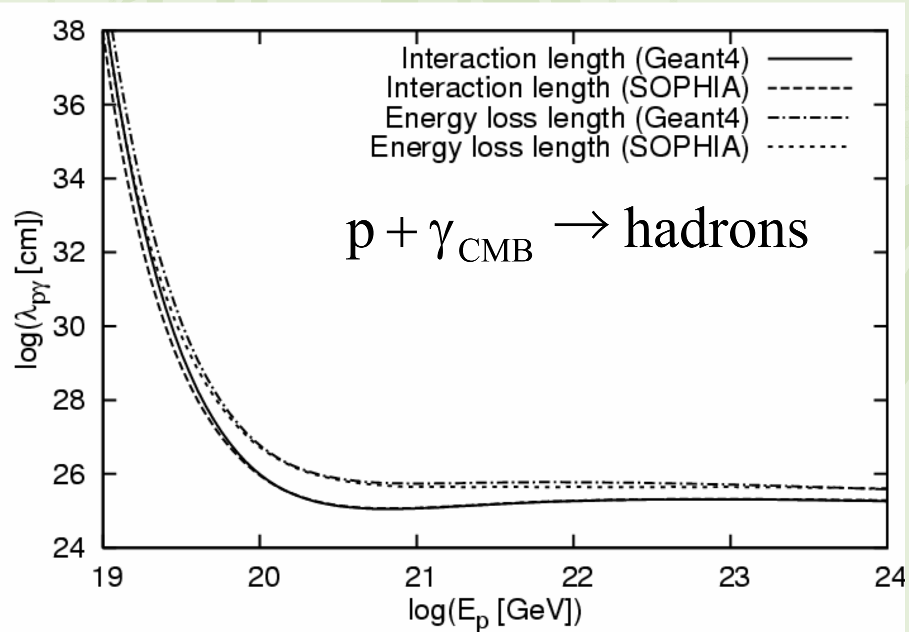


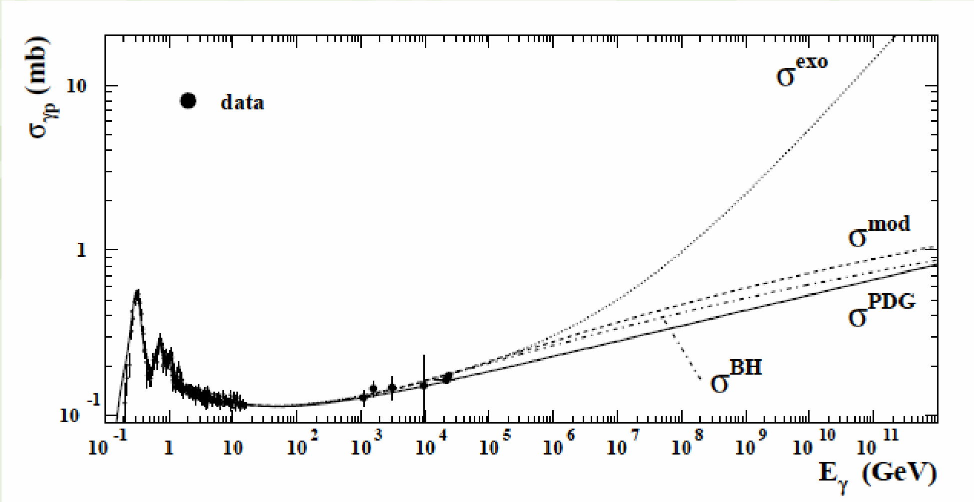
multi-pion production



Geant4 approximation

Experimental data

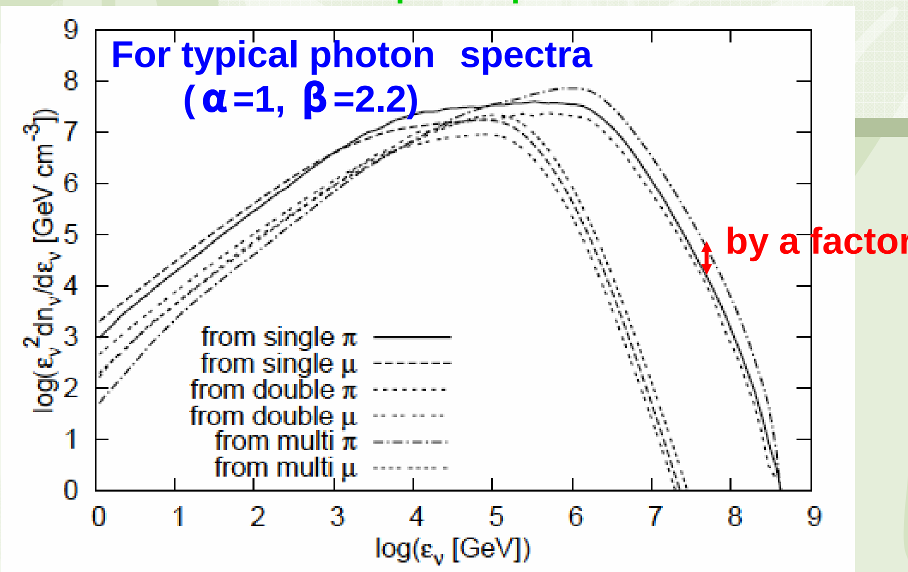


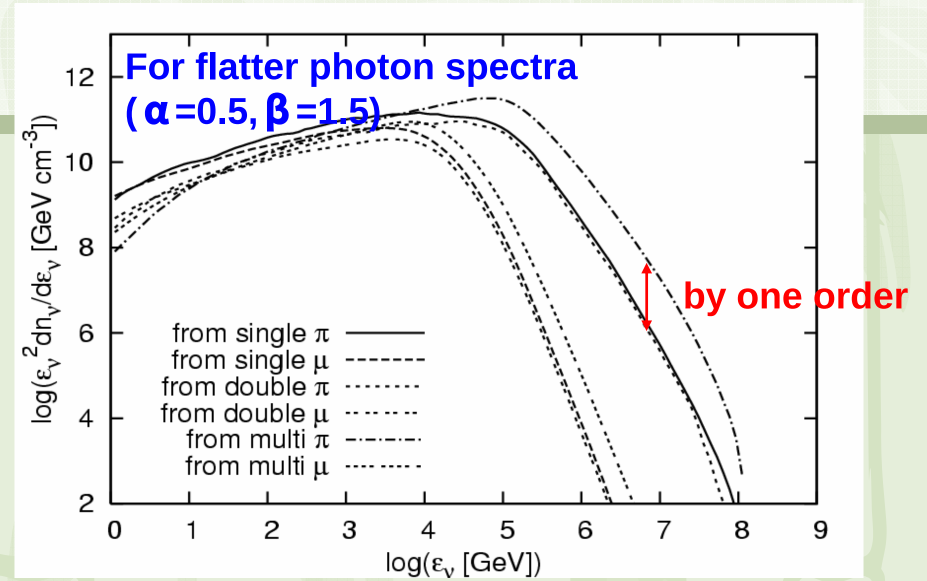


Other Effects

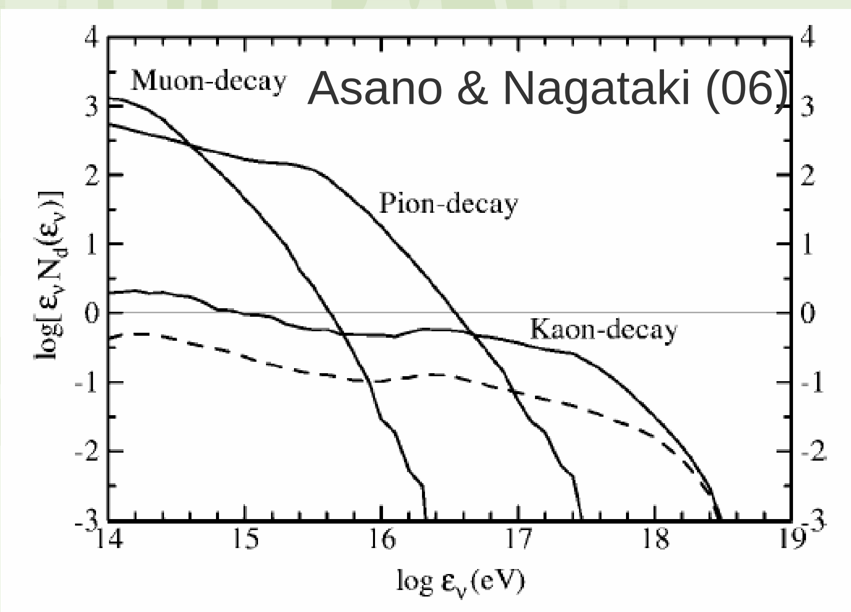
- Effect of multi-pion production

KM & Nagataki, PRD, 73, 063002 (2006)



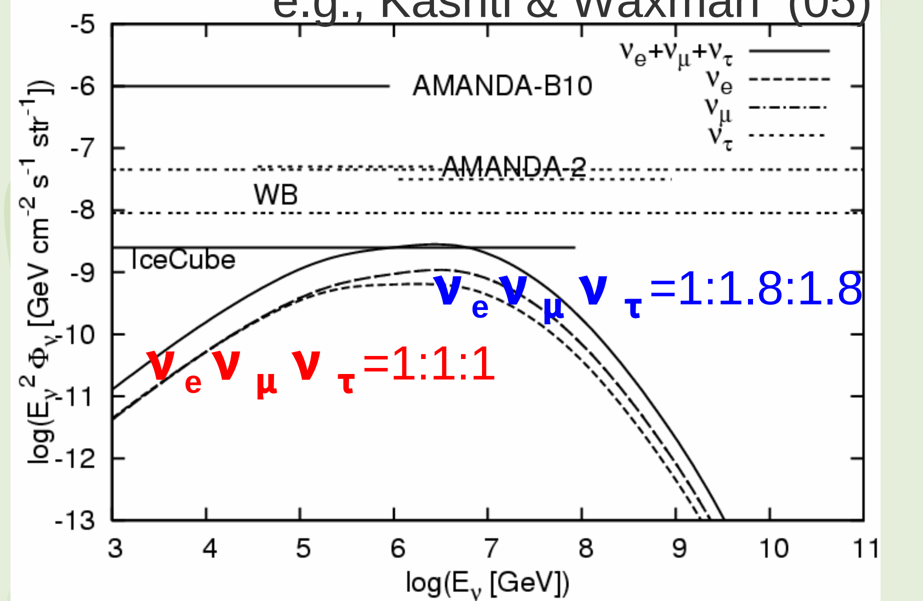


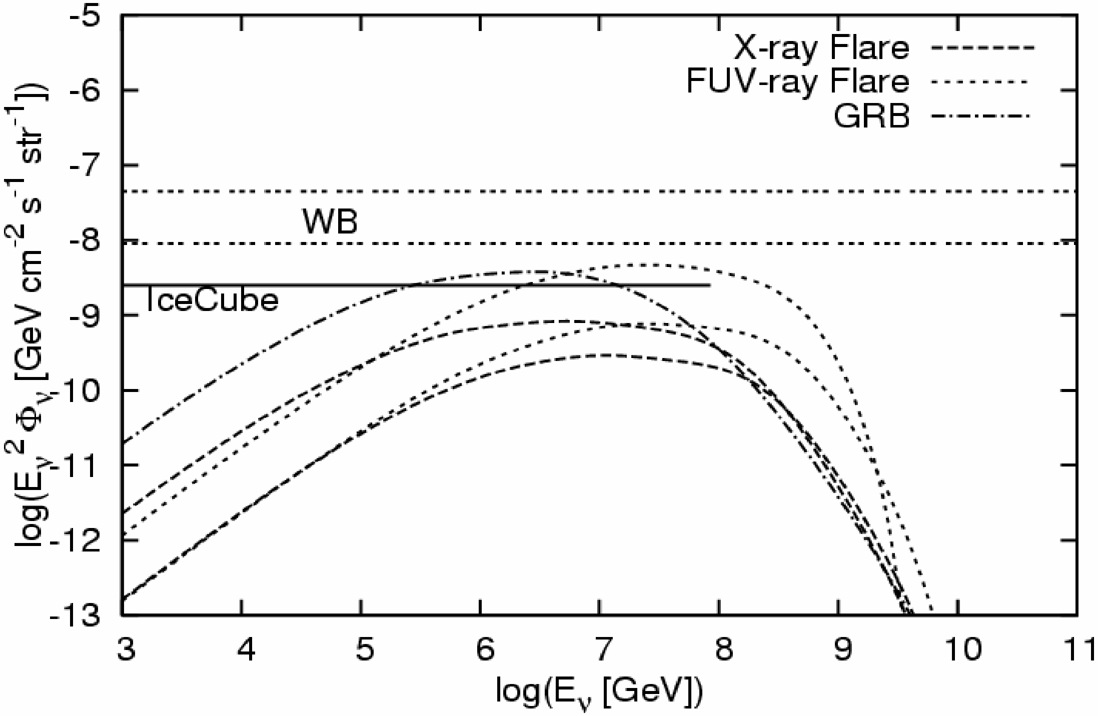
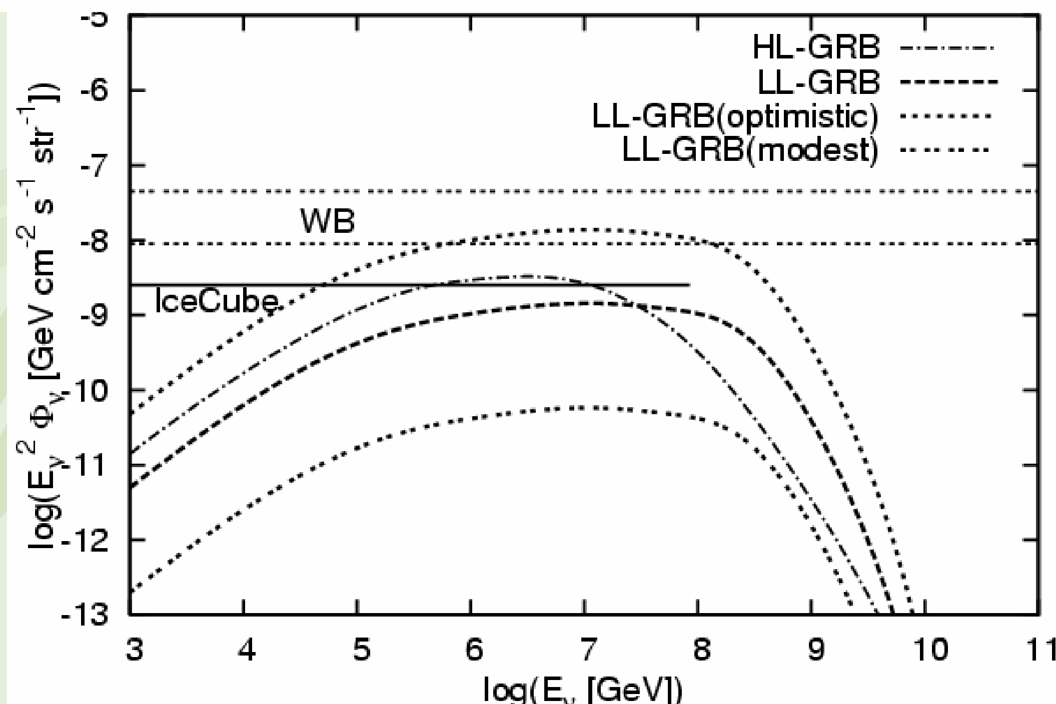
- Effect of Kaon originated neutrinos



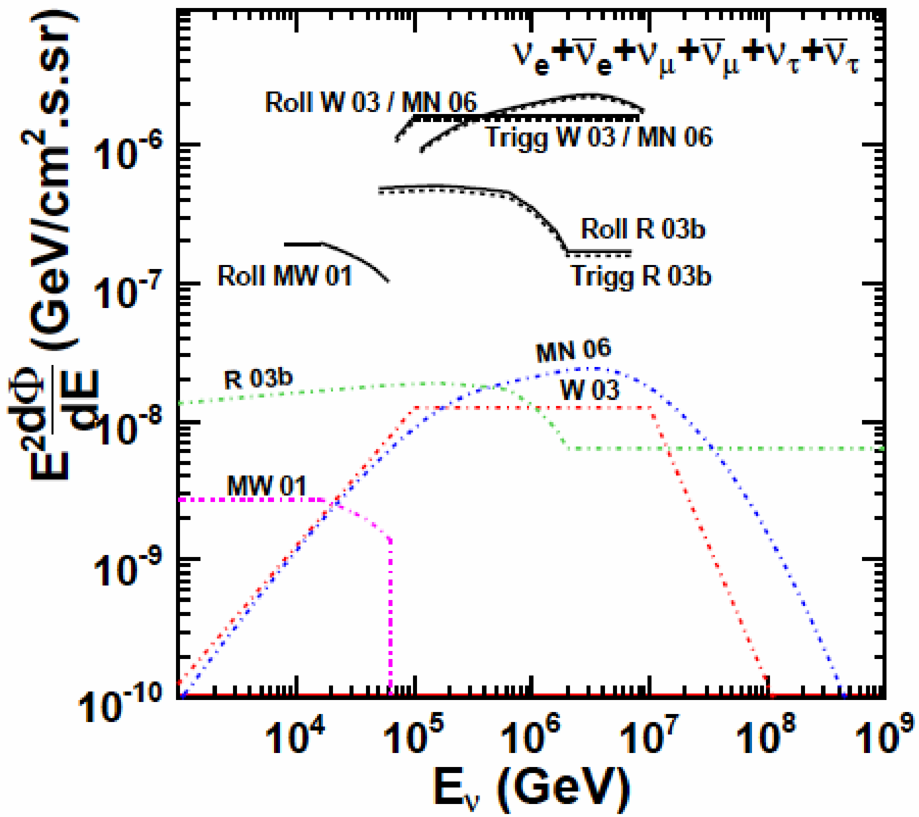
- Effect of neutrino oscillation

e.g., Kashti & Waxman (05)

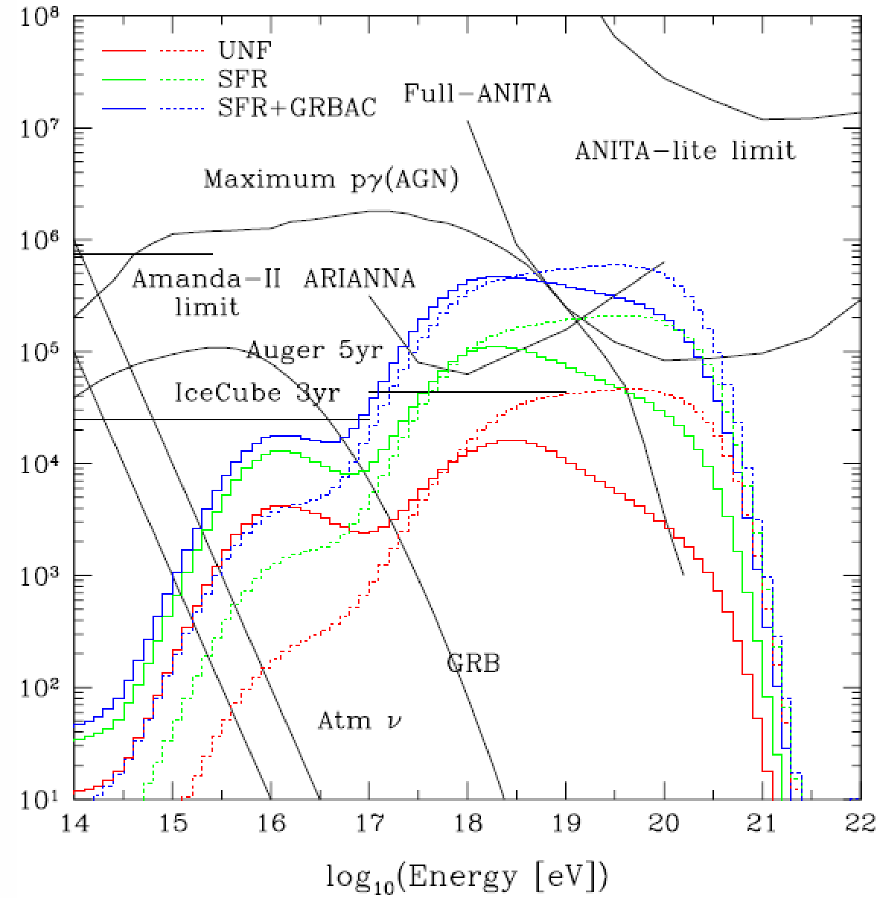



X-ray Flare
FUV-ray Flare
GRB
WB
IceCube
log(E_ν ^2 Φ_ν [GeV cm^-2 s^-1 str^-1])
log(E_ν [GeV])
-5
-6
-7
-8
-9
-10
-11
-12
-13
3
4
5
6
7
8
9
10
11

HL-GRB
LL-GRB
LL-GRB(optimistic)
LL-GRB(modest)
WB
IceCube
log(E_ν ^2 Φ_ν [GeV cm^-2 s^-1 str^-1])
log(E_ν [GeV])
-5
-6
-7
-8
-9
-10
-11
-12
-13
3
4
5
6
7
8
9
10
11

Comparison with other models and GZK νs

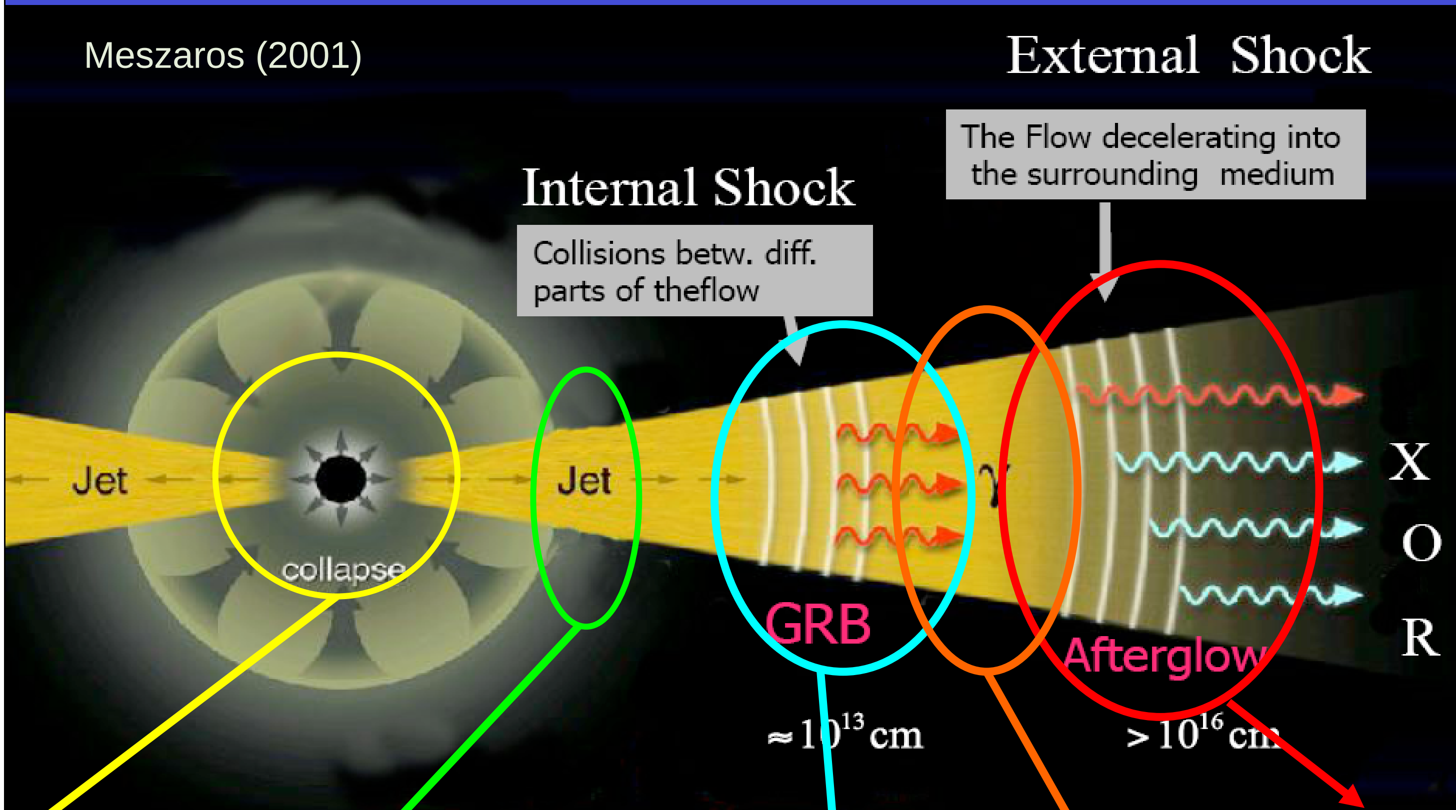


Achterberg et al. (07)
See next talk by Dr. Taboada



Takami, KM, et al., arXiv:0704.0979

Fireball Model: long GRBs



MeV neutrinos
at collapse

TeV neutrinos
from inside the star
(Meszaros & Waxman 2001)
(Schneider et al. 02)
(Razzaque et al. 2003)
(Fabio, KM, et al. 07)

PeV neutrinos
from internal shocks
HL GRBs
(Waxman & Bahcall 1997)
LL GRBs
(KM et al. 2006)
(Gupta & Zhang 2006)

PeV-EeV neutrinos
from flares
(KM &Nagataki 2006)

EeV neutrinos
from external shocks
(Waxman & Bahcall 2000)
(Dermer 2002)
(KM 2007)