High Energy Gamma-Rays and Neutrinos from Gamma-Ray Bursts

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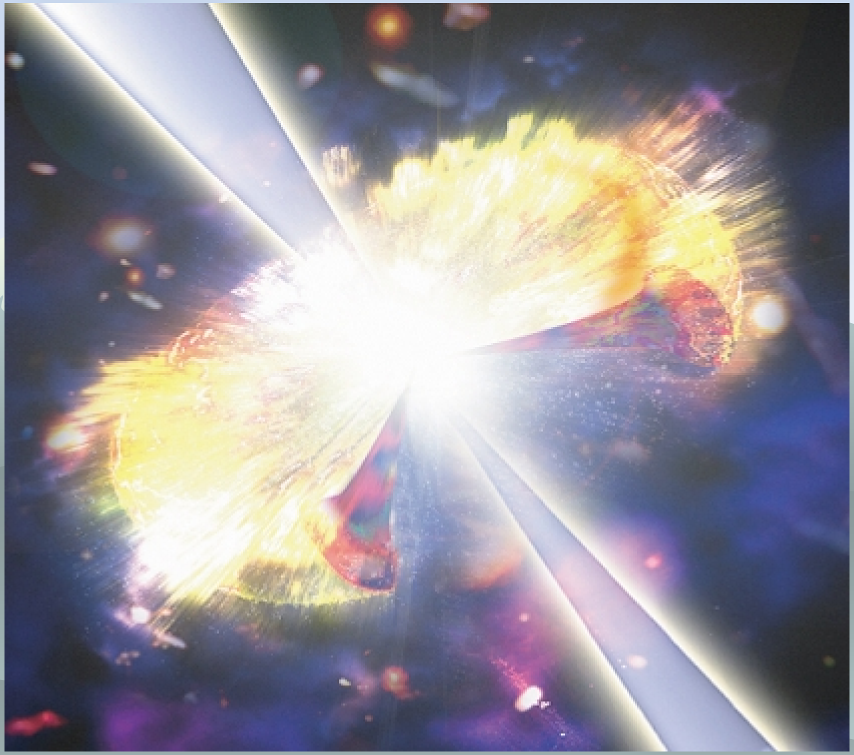
1. ***Introduction***
2. High Energy Emission from GRBs
3. New Predictions in the Swift era
4. Galactic GRBs?
5. Summary

Physics Motivations



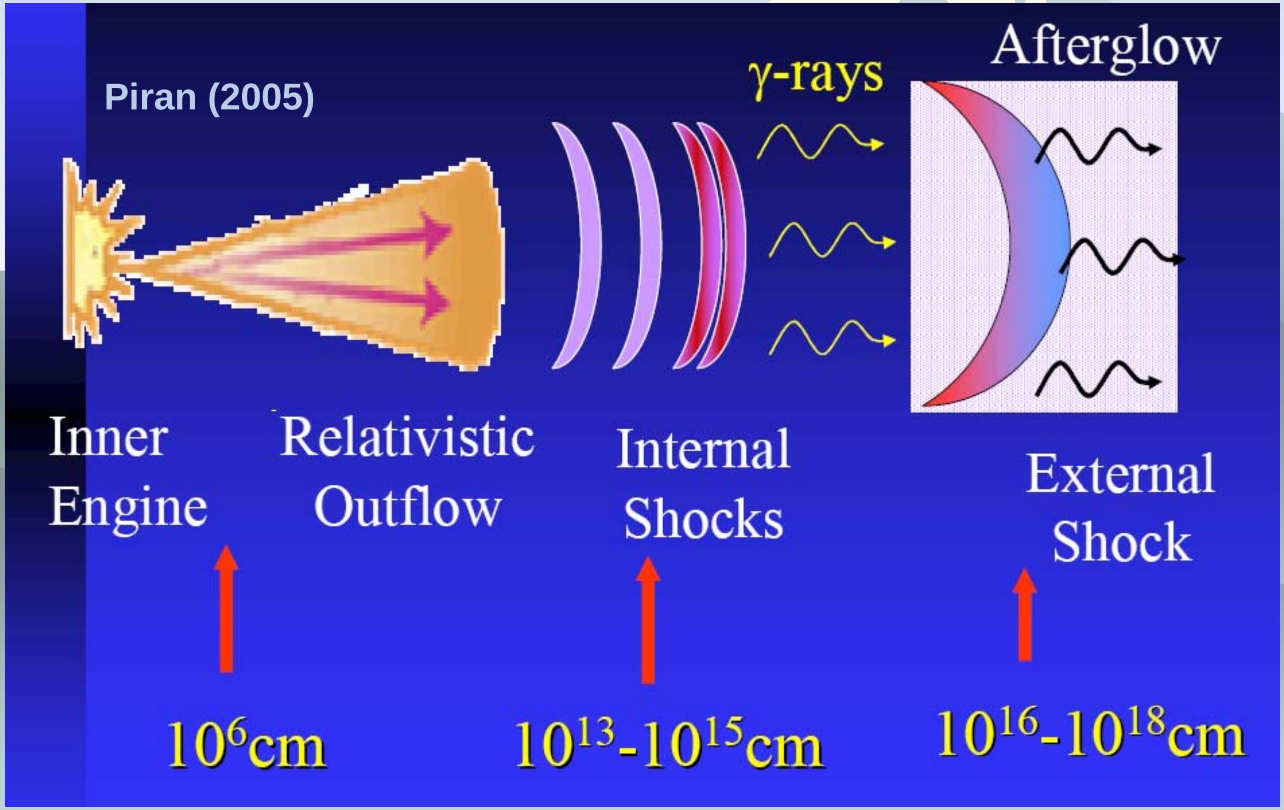
High Energy Gamma-ray and Neutrino Astronomy

Observations by high energy gamma-rays (>GeV)
Observations by high energy neutrinos (>TeV)

•***Information about astrophysical objects (photon density, magnetic field etc.)*** → **We focus on Gamma-Ray Bursts!!**

Gamma-Ray Bursts (GRBs)

- The most energetic phenomena in the universe. L_iso ~10^50-10^54 erg/s。
- Rapid time variability (~1ms-100s). Various duration (~10ms-1000s).
- Long GRBs (T90 > 2 s) and short GRBs (T90 < 2 s)
- Long GRBs ⇔ death of massive stars (← SNe association)
- The central engine of relativistic outflows (probably jets) is still unknown.
- Discovery of afterglow → cosmological phenomena (z~1-3 for long GRBs)



- Standard scenario

Internal shocks

prompt emission

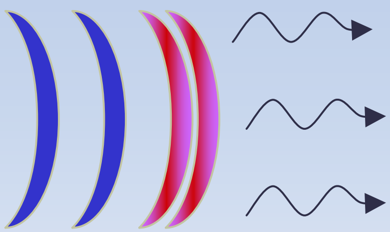
External shock

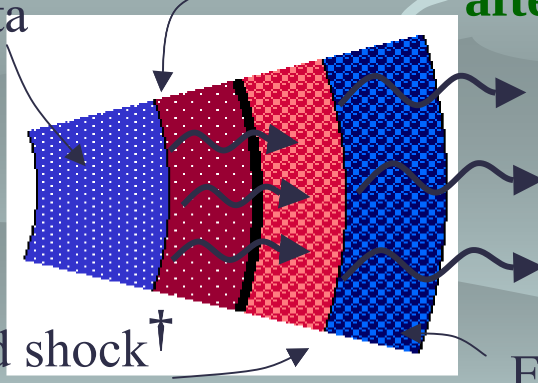
afterglow

The Standard Fireball Model

Goodman 86
Paczynski 86
Shemi & Piran 90, …

(Rees & Meszaros 94, …)





† Meszaros & Rees 92…

†† Meszaros & Rees 92; Katz 94; Sari & Piran 95…

- (Collimated) baryonic flow
- Compactness problem → highly relativistic motion

$$\Gamma > 100$$

Kinetic energy

shock ⇩ *dissipation*

Internal and Magnetic Energy

particle ⇩ *acceleration*

Radiation

Great success of standard synchrotron shock model for explanation of afterglows! (pre-Swift era)

Cartoons from Nakar at HEBU (06)

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•***Smoking gun for baryon acceleration***

↑ ***high energy γs and νs through pγ and pp reactions***

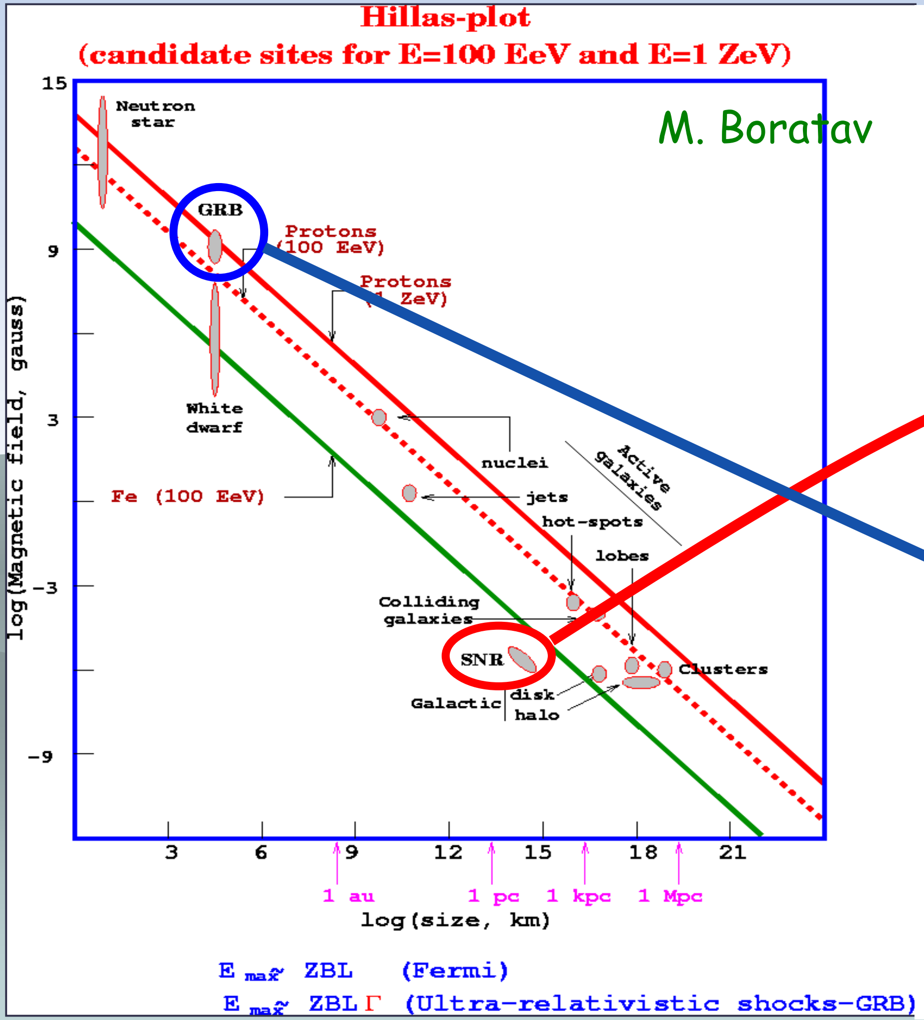
Neutrinos as the stronger evidence for acceleration.

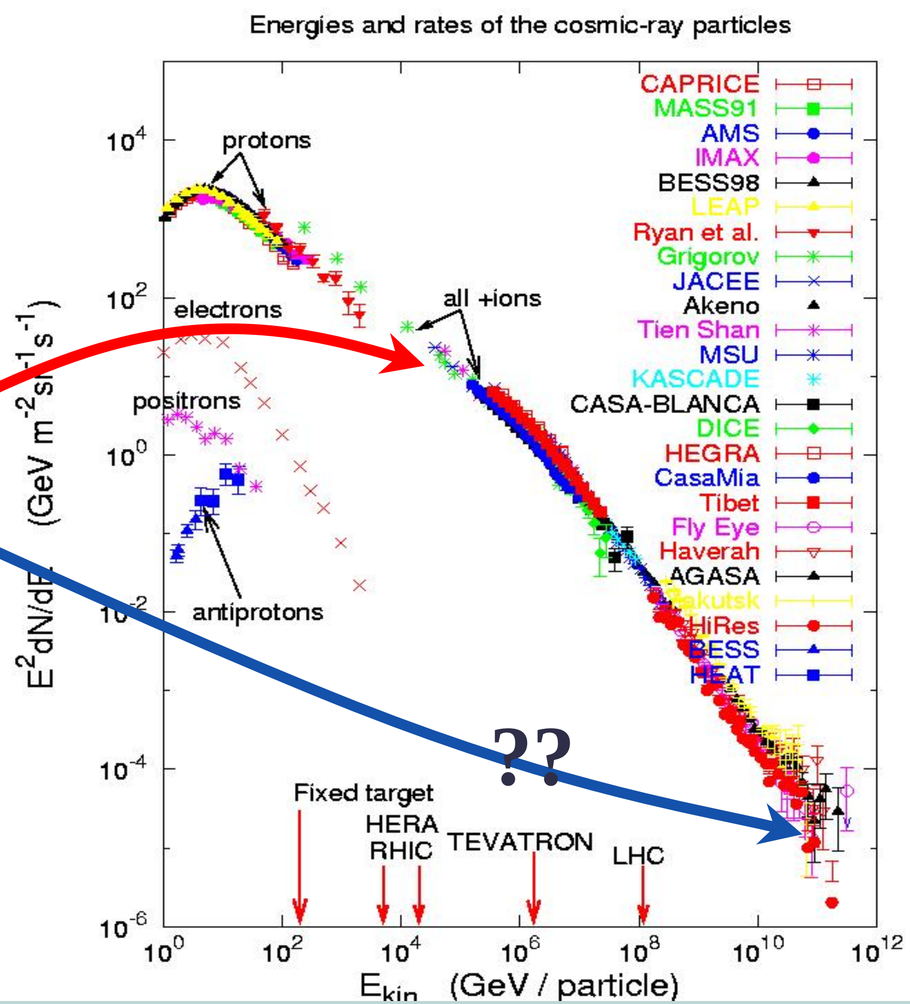
The probe for poorly unknown acceleration mechanism

The clue for main acceleration sites of (U)HECRs

Ultra-High-Energy Cosmic Ray Connections

What is the main source of UHECRs? → GRBs?, AGNS?,
(within bottom-up scenarios) Starburst Galaxies?
Clusters of Galaxies?





Theoretical Predictions

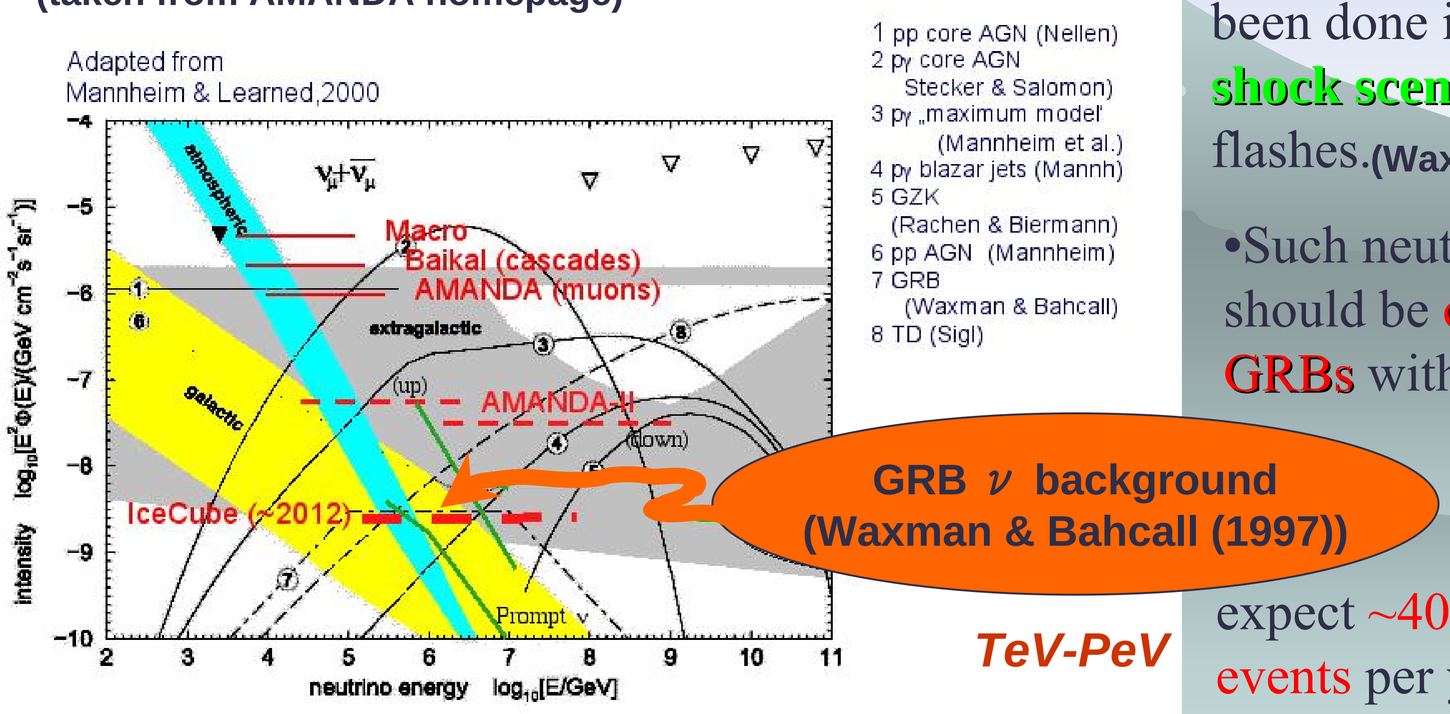
GRBs could be one of the candidates for main sources of UHECRs

Waxman (95), Vietri (95)

Waxman & Bahcall predicted neutrino bursts **assuming that observed UHECRs can be explained by GRBs** (i.e. normalized GRB proton flux by observed UHECRs flux) **Waxman & Bahcall (97)**

Diffuse Fluxes - Predictions and Limits

(taken from AMANDA homepage)



- Similar predictions have been done in the **reverse shock scenario** for optical flashes. **(Waxman & Bahcall (00))**
- Such neutrino bursts should be coincident with GRBs within durations.
- If true, we can expect ~40 muon-neutrino events per yr by IceCube.

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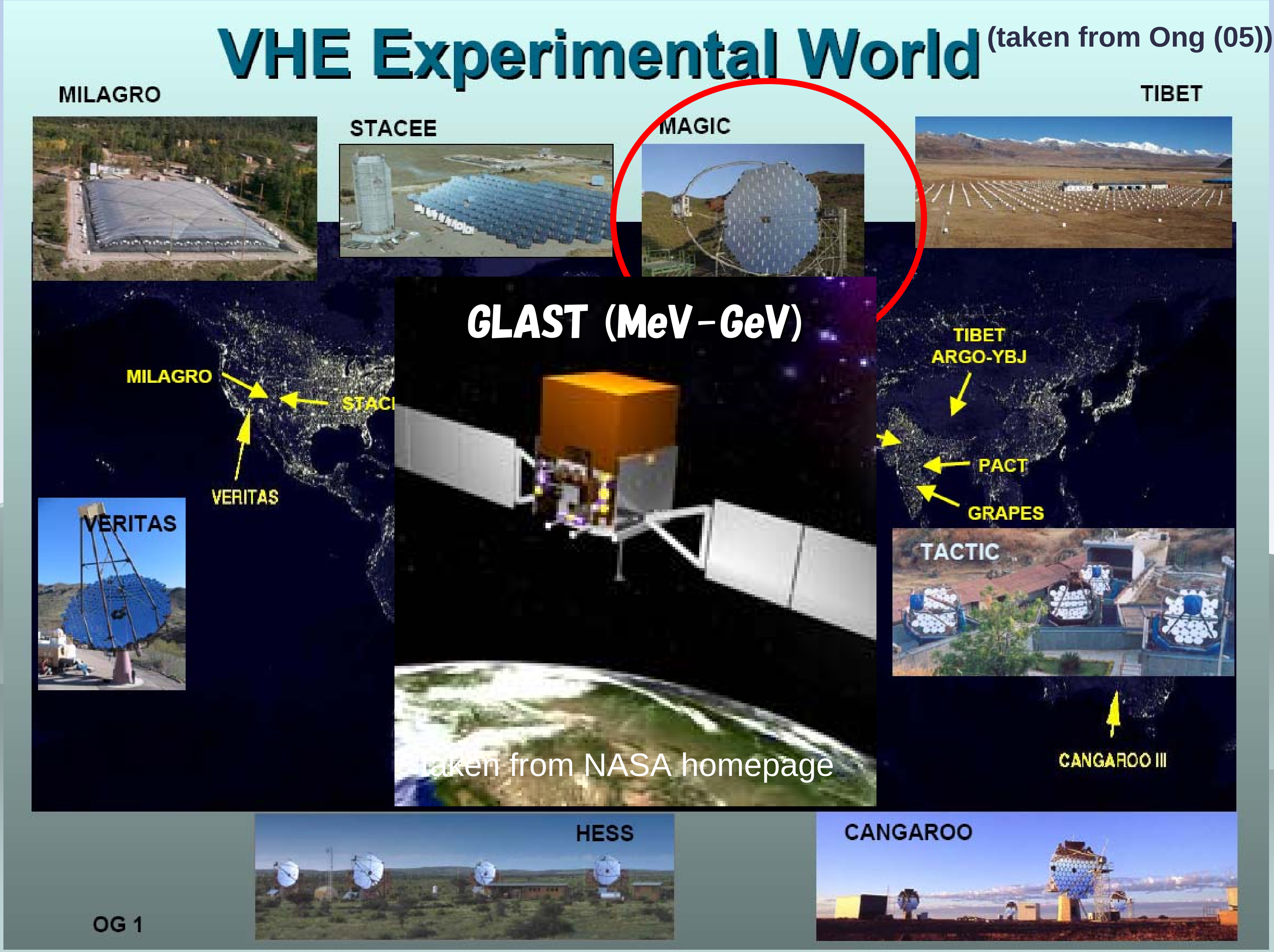
•Smoking gun for baryon acceleration
↑ ***high energy γs and νs through p γ and pp reactions***
Neutrinos as the stronger evidence for acceleration.
The probe for poorly unknown acceleration mechanism
The clue for main acceleration sites of (U)HECRs

•New detectors will be available in the near future.
•High energy neutrino physics using such detectors.

High Energy Gamma-Ray Detectors



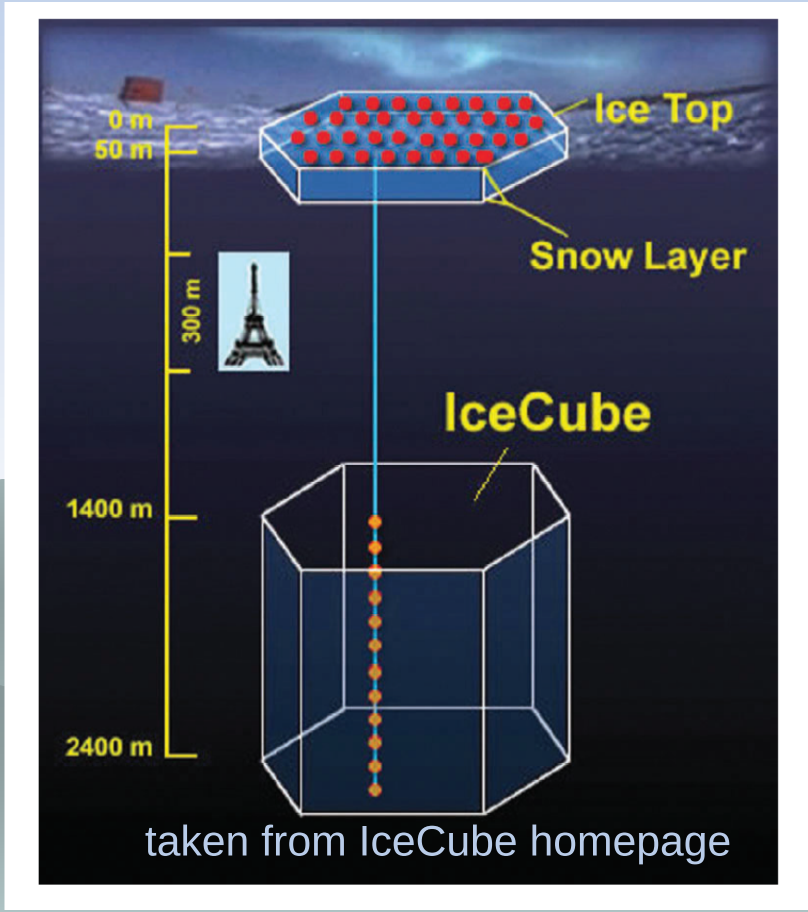
Future Neutrino Detectors

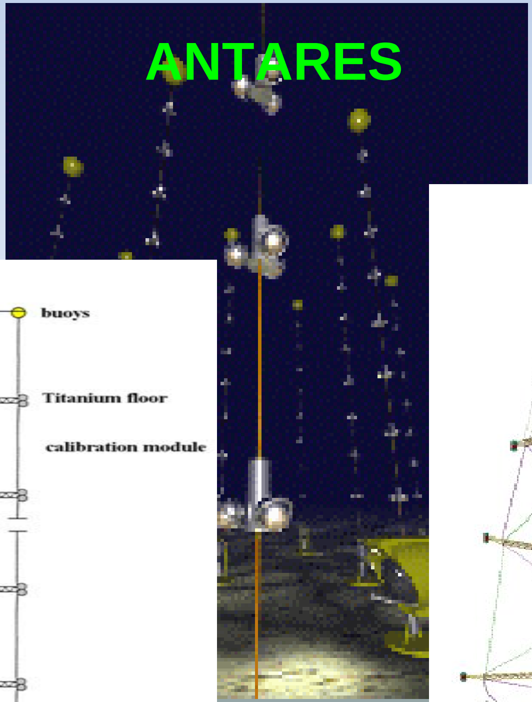
IceCube (Antarctica)

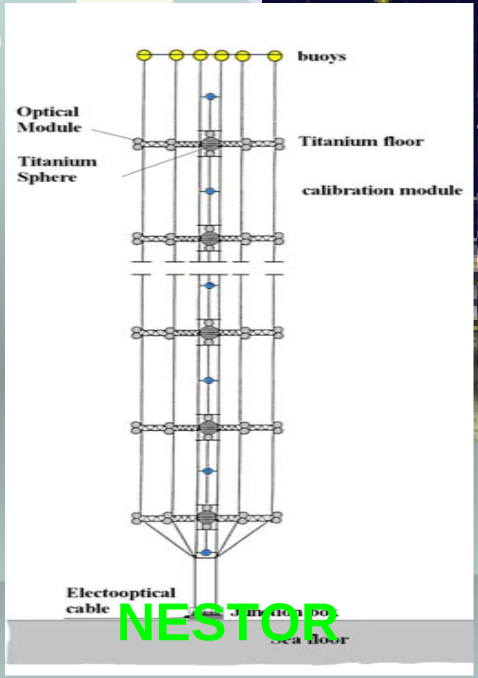
Km3 ice Cherenkov

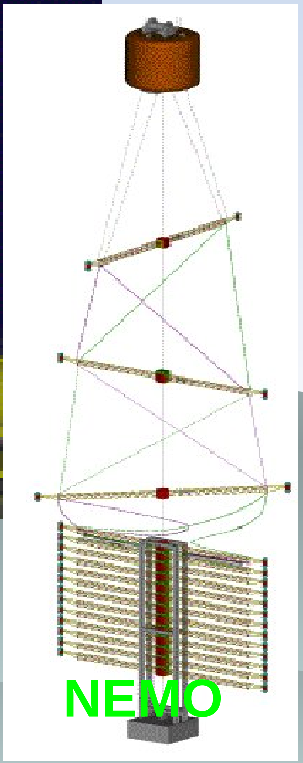
KM3 (Mediterranean)

Km3 water Cherenkov









Complementary sky coverage!

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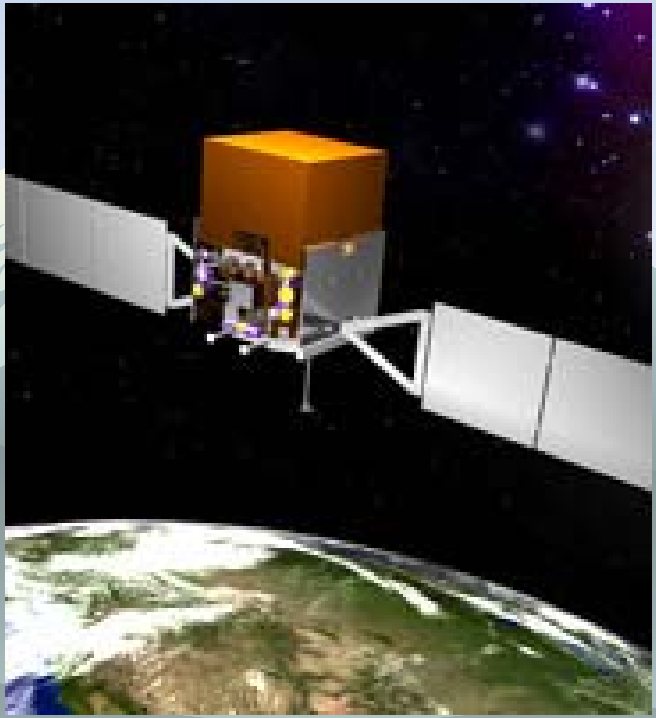
High Energy Gamma-Rays from GRBs



High Energy Emission from GRBs

◆ Leptonic Models

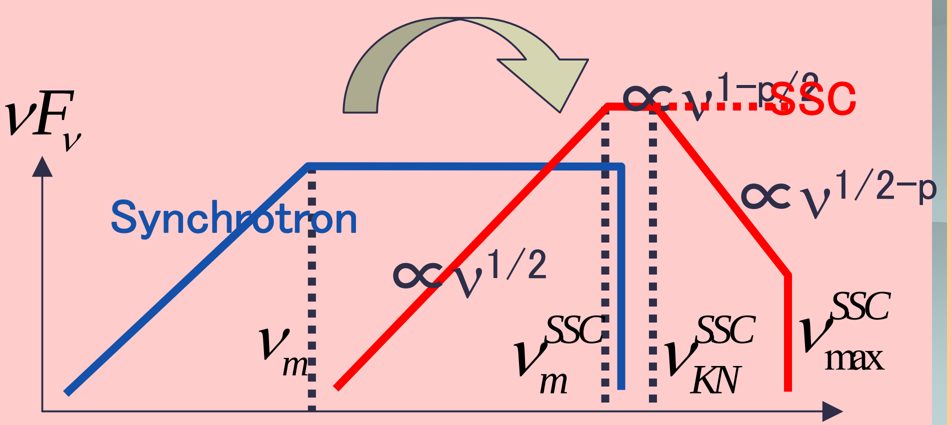
1. Electron synchrotron

e.g. Sari, Piran & Narayan (98)

2. Synchrotron Self-Compton

Sari & Esin (01), Zhang & Meszaros (01), Guetta & Granot(03), Peer & Waxman (04)

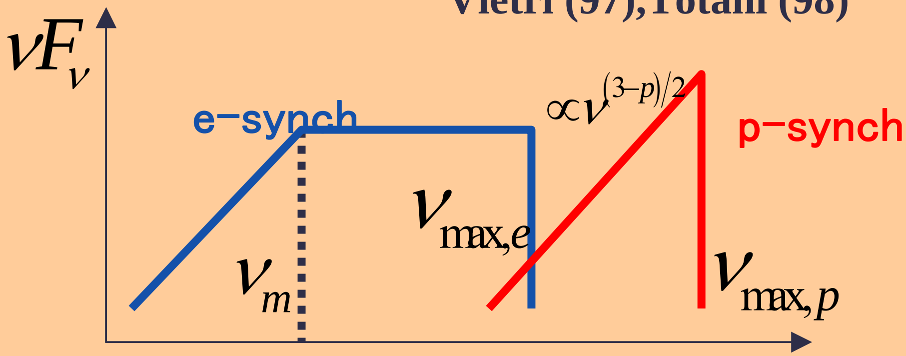
$$Y \equiv \frac{L_{SSC}}{L_{syn}} \sim \begin{cases} \sqrt{\varepsilon_e / \varepsilon_B} & (\varepsilon_e >> \varepsilon_B) \\ \varepsilon_e / \varepsilon_B & (\varepsilon_e << \varepsilon_B) \end{cases}$$



◆ Hadronic Models

3. Proton synchrotron

Vietri (97),Totani (98)



4. Neutral pion decay produced by *photo-meson production*

5. The contribution from electrons+positrons produced by *photo-pair production*

Waxman & Bahcall(97), Vietri(98), Bottcher & Dermer (98), Dermer & Atoyan (04) Peer & Waxman (05), Asano & Inoue in prep.

>MeV Emission from Internal Shocks

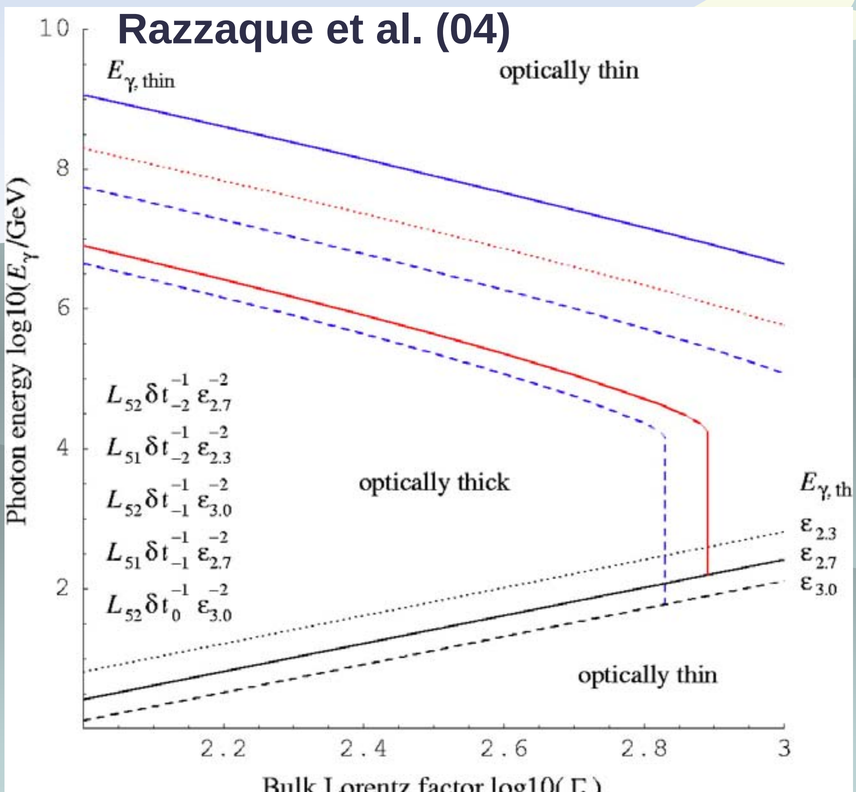
Low energy photons ← **synchrotron self-absorption**

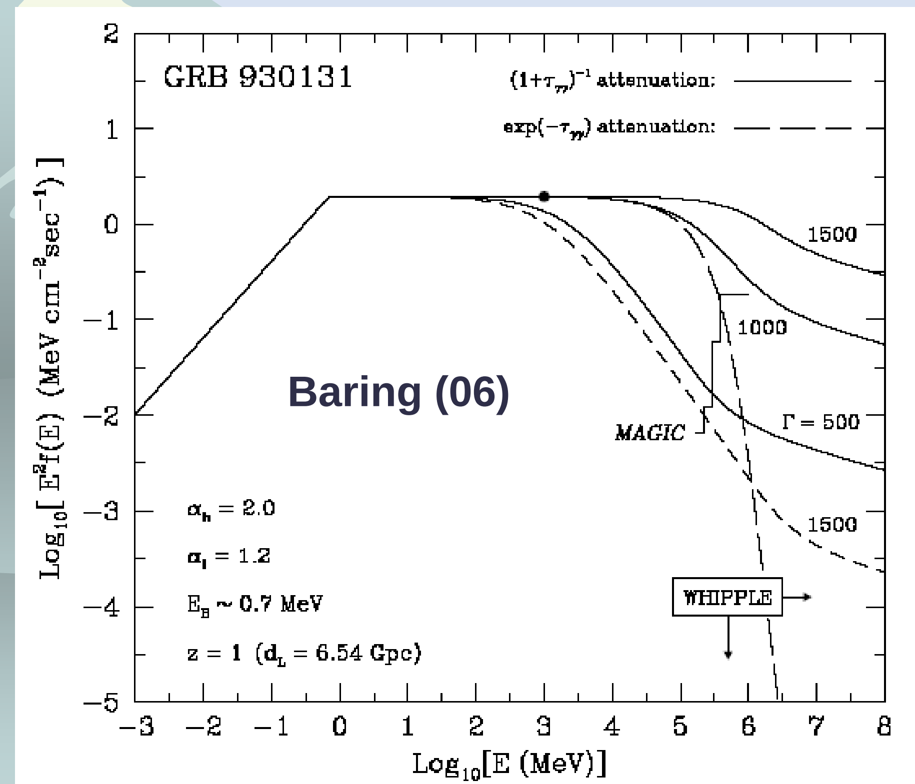
High energy photons ← pair creation (γ γ →pairs or γ e→e+pairs)

Very High Energy Photons ← γ γ suppression + self-absorption

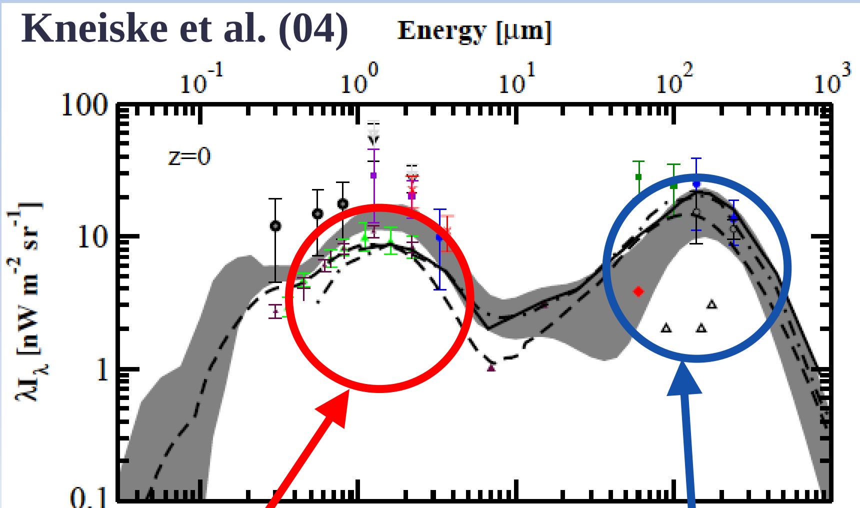
$E_{\gamma,th} \sim 26\ \Gamma_{2.5}^{2}\ \varepsilon_{\gamma,2.7}^{-1}$ GeV

$E_{\gamma,thin} \sim 2\times10^{7}\, \Lambda_{3}\, L_{\gamma,52}\, \Gamma_{2.5}^{-2}\, \delta t_{-2}^{-1}\, \varepsilon_{\gamma,1}^{-2}$ GeV



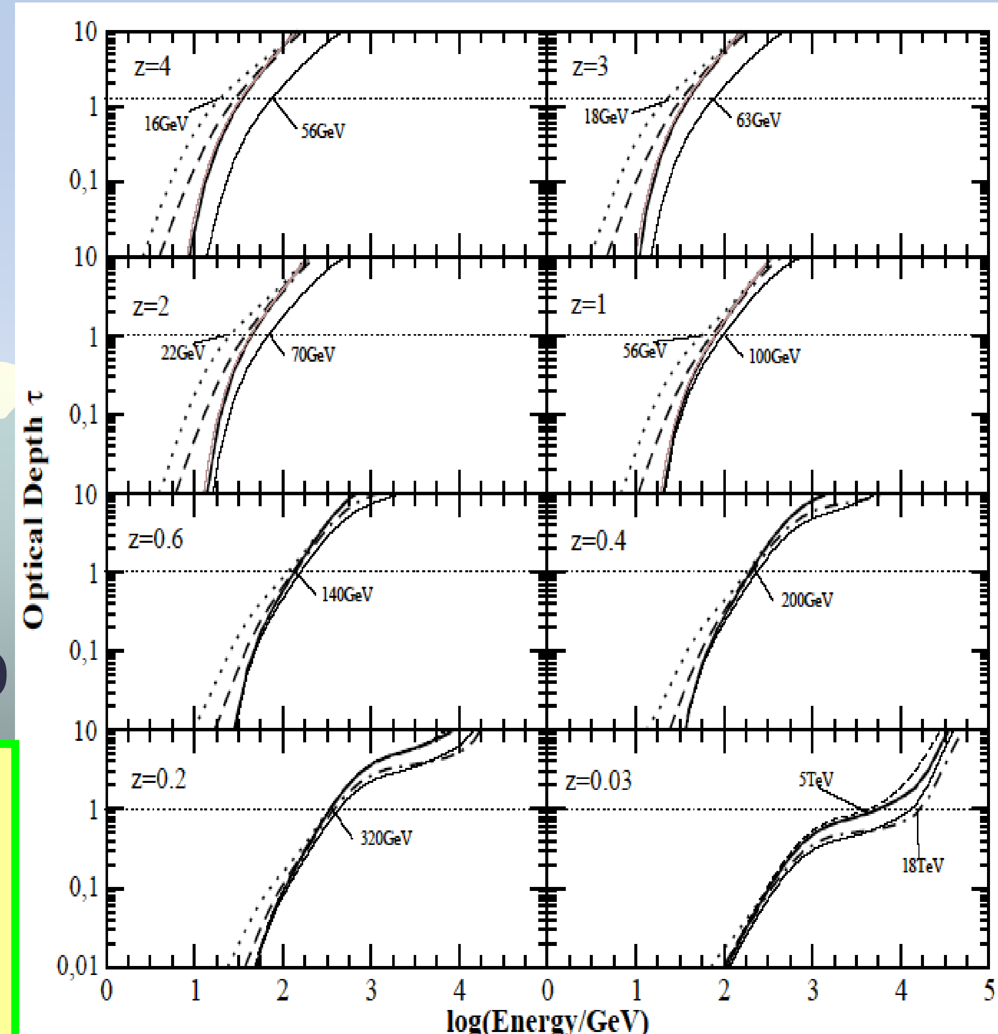


Attenuation by Cosmic Infrared Background



Massive stars
(MS life < 0.3Gyr)

Low mass stars
(MS life > 0.3 Gyr)



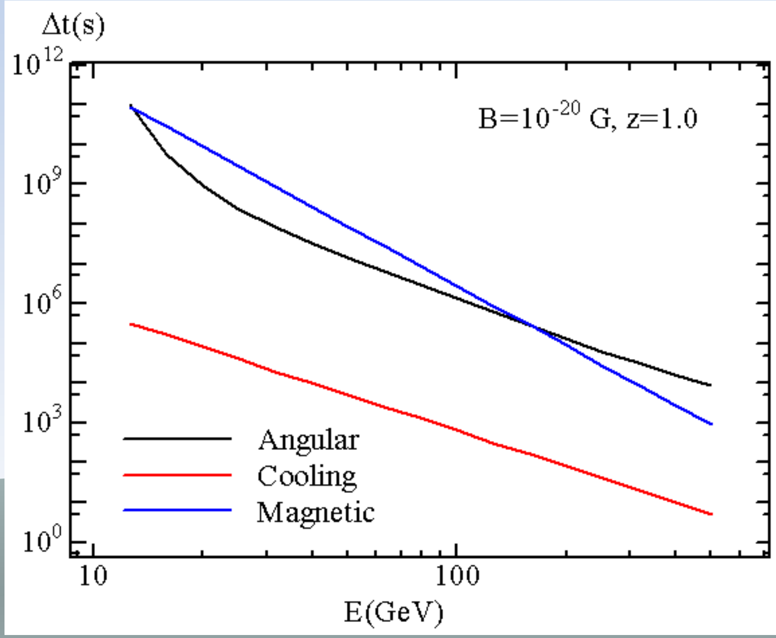
↑ **Optical thickness for photons**

~TeV γ rays cause pair-creation with CIB photons.
~PeV γ rays cause pair-creation with CMB photons.

※ **TeV observations can *constrain* CIB which has large observational uncertainty** (e.g. Aharonian e al. (06))

Delayed Emission

•We assume intrinsic spectra extended to TeV range.
→Pairs can be created by interactions with CIB and CMB.
→Secondary spectra form by scattering off CMB and CIB.



Secondary emission from GRBs will be delayed due to…

1. Angular spreading
2. Magnetic deflection
3. Inverse Compton cooling

Too long delay time leads to no detection. Especially, **intergalactic magnetic field** is **very important**. (we assume B>10^-20 G)

Dai & Lu (02), Guetta & Granot (03), Razzaque et al.(04)

We are performing **the most detailed calculations** of delayed spectra using ***Monte Carlo Method*** (**KM, Asano & Nagataki (06) in prep.**)

1. pair creation 2. Compton scattering 3. synchrotron cooling included

→ We can treat **electromagnetic cascading process!**

→ Possible detections by **GLAST**, **MAGIC** and so on

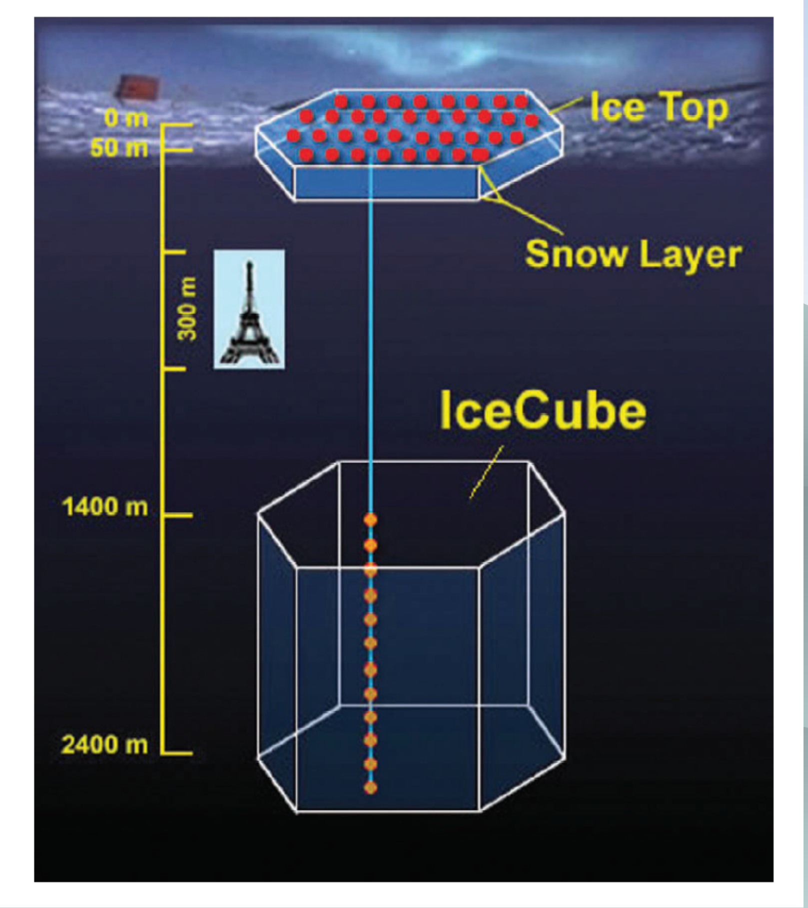
→ Information about sources (e.x. magnetic field), CIB, intergalactic B etc…

Primary and Secondary Spectra from GRBs

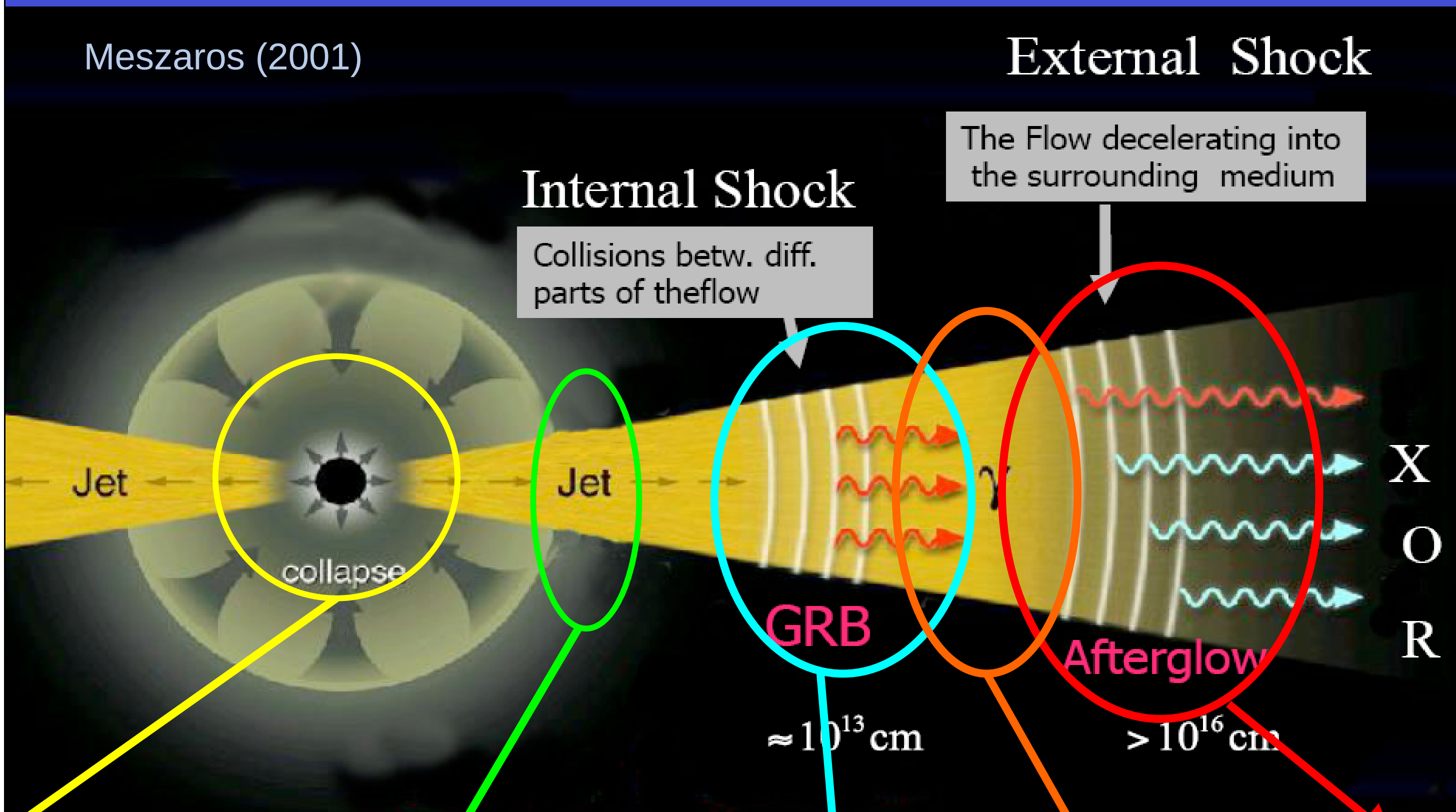
KM, Asano & Nagataki (06), in prep.

現在準備中です。
2006年11月頃までお待ち下さい。

High Energy Neutrinos from GRBs



Fireball Model: long GRBs



MeV neutrinos
at collapse
(e.g. Halzen & Jaczko 1998)

TeV neutrinos
from inside the star
(Meszaros & Waxman 2001)
(Razzaque et al. 2003)

PeV neutrinos
from internal shocks
(Waxman & Bahcall 1997)
(KM & Nagataki 2006)
(Gupta & Zhang 2006)

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

EeV neutrinos
from external shocks
(Waxman & Bahcall 2000)
(Dermer 2001)

What's New? & Calculation Method

What's New?

- Energy spectra of high energy neutrinos from a GRB and GRBs are calculated more quantitatively with detailed microphysics and recently suggested GRB rate.

1. **Multi-pion production effects by *Geant4*.**
2. **Energy loss due to synchrotron cooling, inverse Compton cooling, and adiabatic cooling of charged pions and muons.**
3. **Even if GRBs *cannot* supply enough UHECR, there should be possibilities that high energy neutrinos are produced in GRBs and detected by IceCube.**

(KM and Nagataki, PRD, 73, 063002 (06))

- We propose new possibilities, suggested by recent observations of Swift, that we can detect high energy neutrinos from GRBs.

FUV/X-ray flares in the early afterglow phase → Neutrino Flashes

(KM and Nagataki, PRL, 97, 051101 (06))

Low-luminosity GRBs (LL-GRBs) → Neutrino bursts from LL-GRBs

(KM, Ioka, Nagataki, Nakamura, ApJL, submitted (06))

Calculation Method

Giving comoving **photon spectra** from observed photon spectra → Giving **proton spectra** (with the evaluated **maximum energy** and introducing the **nonthermal baryon-loading factor**) → Calculating **pion spectra** from pγ reactions by ***Geant4*** and following **neutrino spectra** including **meson and muon cooling** → Evaluating **(diffuse) neutrino background** using GRB rate history

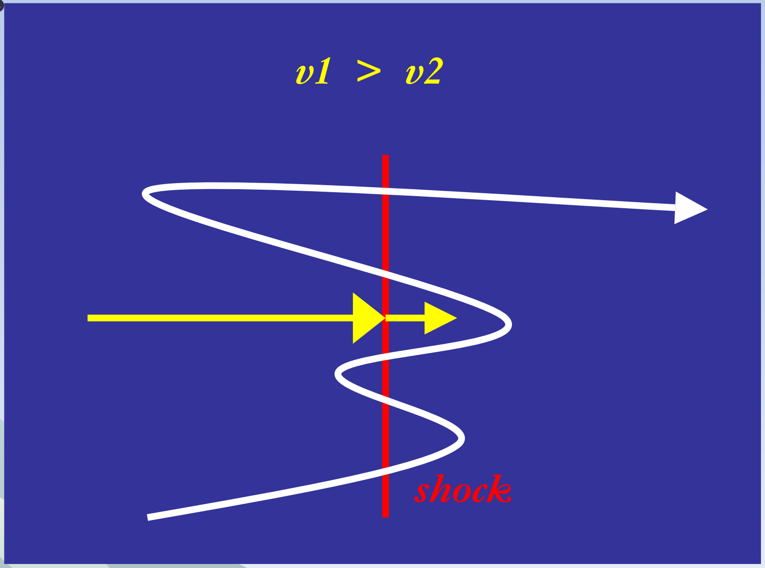
Cosmic Ray Acceleration in GRBs

Acceleration mechanism in relativistic shocks is poorly known theoretically.

- ***First-order Fermi acceleration*** is one of plausible mechanisms.

For mildly relativistic shocks such as internal shocks (and/or reverse shocks), **the UHECR -acceleration could be possible.** **(Waxman 95)**

For ultra-relativistic shocks such as forward shocks, **the UHECR-acceleration will not occur?**
(Gallant & Achterberg 99, Milosavljevic & Nakar 05)



Shock acceleration

Criterion of Acceleration

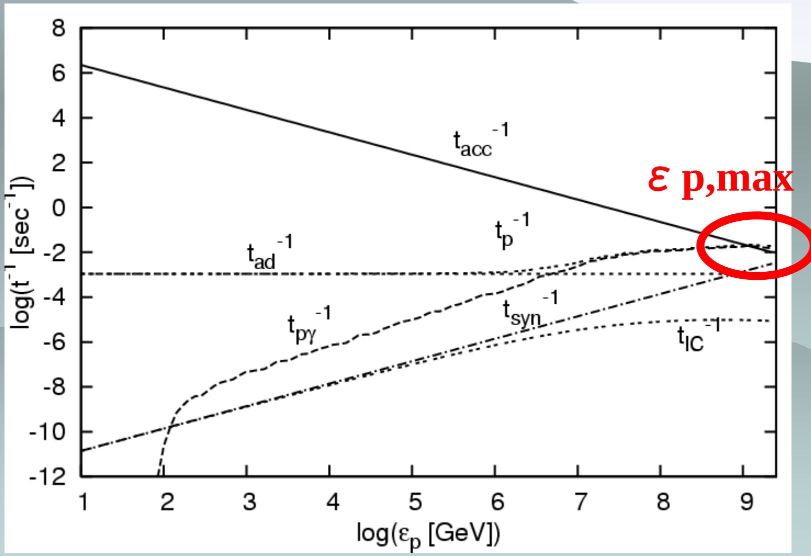
$$t_{acc} < t_{cool}$$

$$\left(t_{acc} = \eta \frac{\varepsilon_p}{eBc} \quad (\eta \sim 1-10)\right)$$

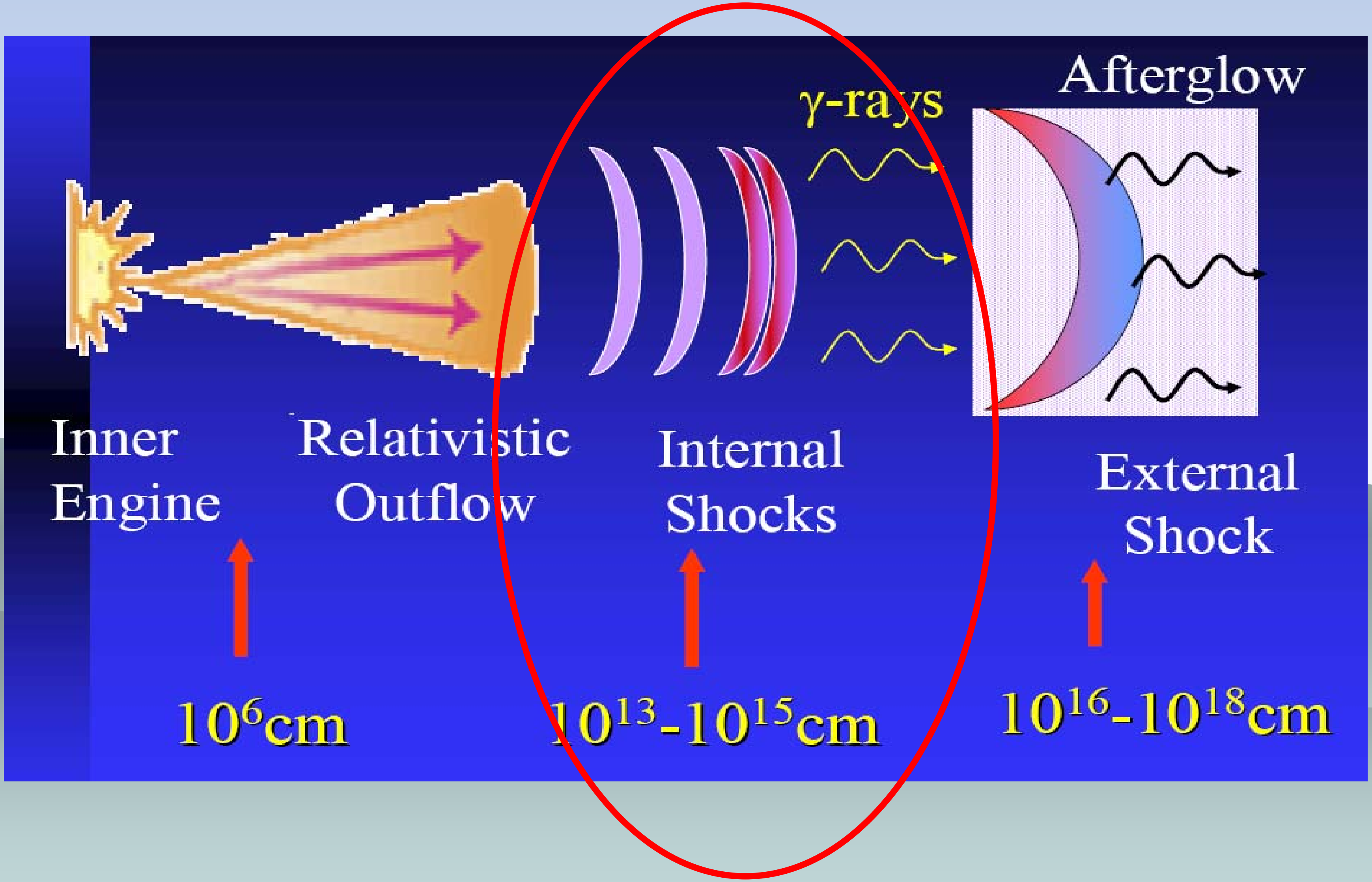
+
(Hillas condition)

Cooling Process
- photomeson production
- synchrotron radiation
- inverse Compton scattering
- adiabatic loss

etc.



Neutrino Bursts from Prompt Emission



Internal Shock Model

Kinetic energy of subshells with $\Gamma \sim 300$

→ **Nonthermal Energy** → ***prompt emission***

Mildly relativistic shocks

Typical parameters

Total energy $E_\gamma = \frac{\theta^2}{2} E_\gamma^{iso} \sim 10^{51}$ ergs

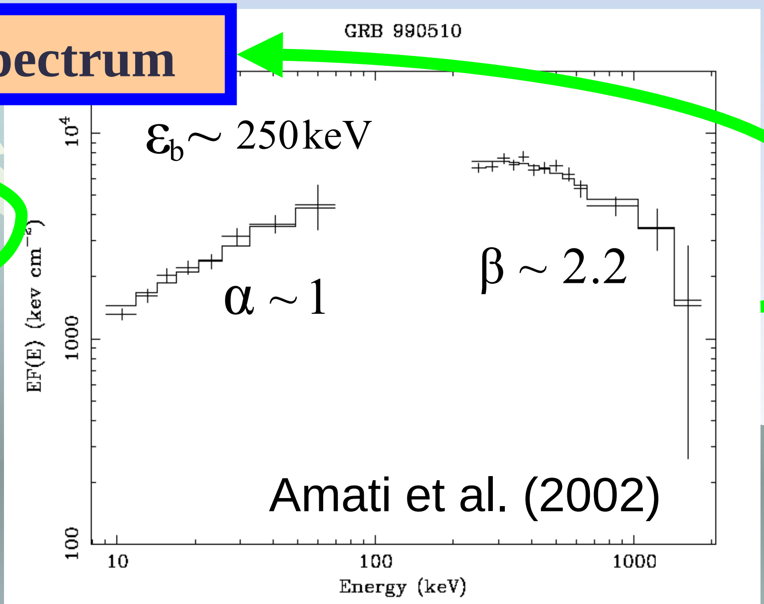
Isotropic energy $E_\gamma^{iso} \sim (10^{52} - 10^{54})$ ergs

Isotropic energy per subshell $E_{\gamma,sh}^{iso} \sim (10^{48} - 10^{53})$ ergs

Collision radii $r \sim (10^{13} - 10^{15.5})\ cm$

Typical width of subshells $l (\sim r / \Gamma)$

Photon spectrum



We introduce the **nonthermal baryon loading factor** (which ***nobody knows now*** but ν observations can constrain) instead of normalizing by observed UHECR flux.

Accelerated proton energy $U_p = \xi_{acc} U_\gamma \approx \xi_{acc} U_e$

Proton spectrum $\frac{dn_p}{d\varepsilon_p} \propto \varepsilon_p^{-2}$

Photomeson Production

p γ-reaction

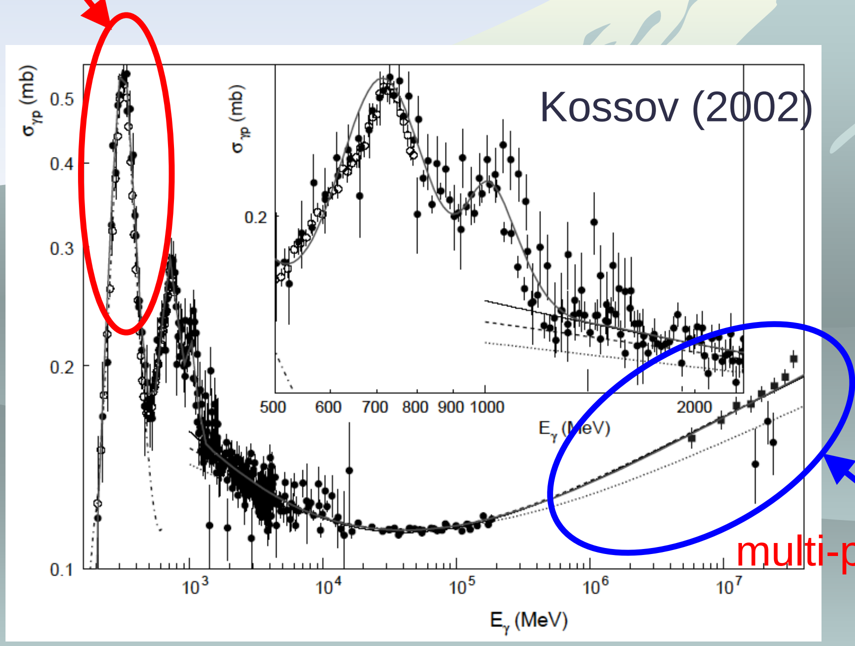
$$p+\gamma \rightarrow \Delta \rightarrow n+\pi^+ \quad \kappa_p \sim 0.2$$ Δ-resonance

$$p+\gamma \rightarrow N\pi^\pm + X \quad \kappa_p \sim (0.5-0.7)$$ multi-pion production

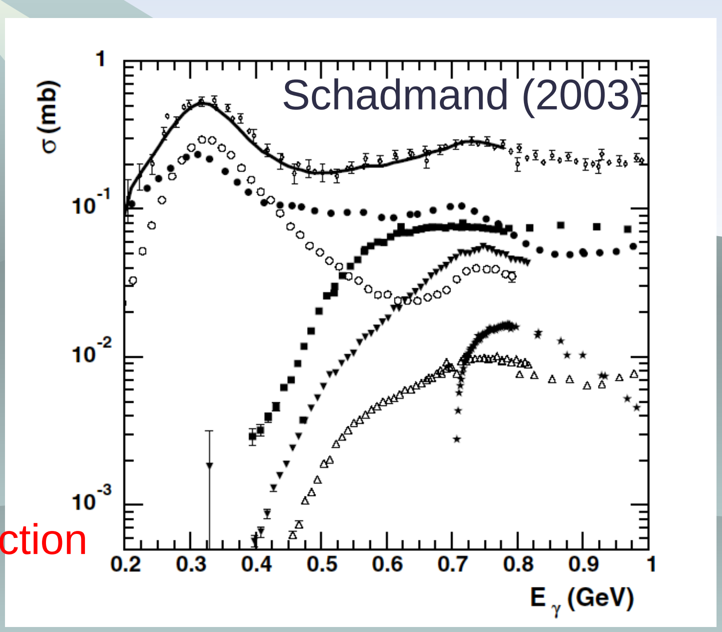
Geant4

Multiplicity + Inelasticity

Δ-resonance



multi-pion production



Geant4 approximation

Experimental data

TeV-PeV Neutrinos from Internal Shocks

p γ

$$p+\gamma \to \Delta \to n+\pi^{+} \quad \kappa_p \sim 0.2$$

$$p+\gamma \to N\pi^{\pm}+X \quad \kappa_p \sim (0.5-0.7)$$

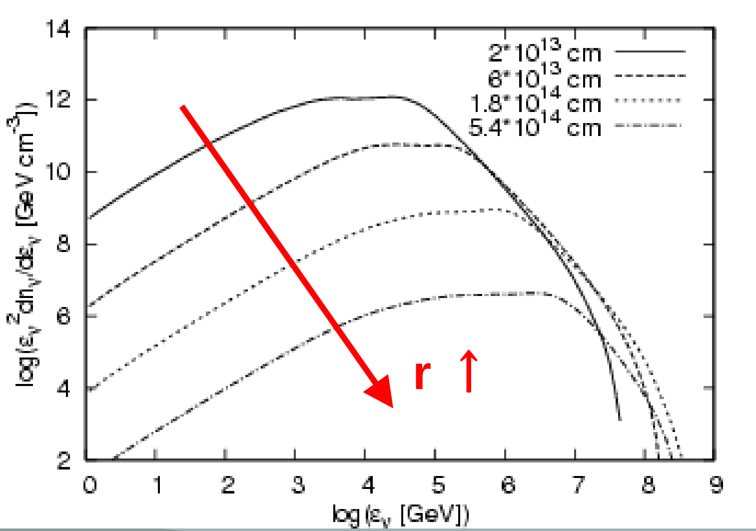
Geant4

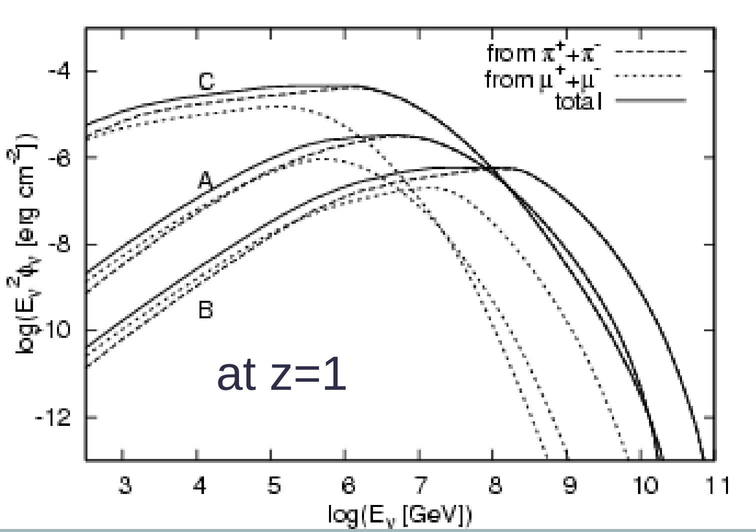
Multiplicity + Inelasticity

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

Cooling Processes

- **Synchrotron Loss**
- **Adiabatic Loss**
- **Inverse Compton Loss**





•At collision radii < 10^14 cm, a fireball can be optically thick to p γ production and accelerated protons will be depleted . At larger radii, UHECRs can be produced (Asano 2005) and ν 's energy can be higher.

•Neutrino signals only from energetic or near bursts can be detected by IceCube. (Dermer & Atoyan 2003)

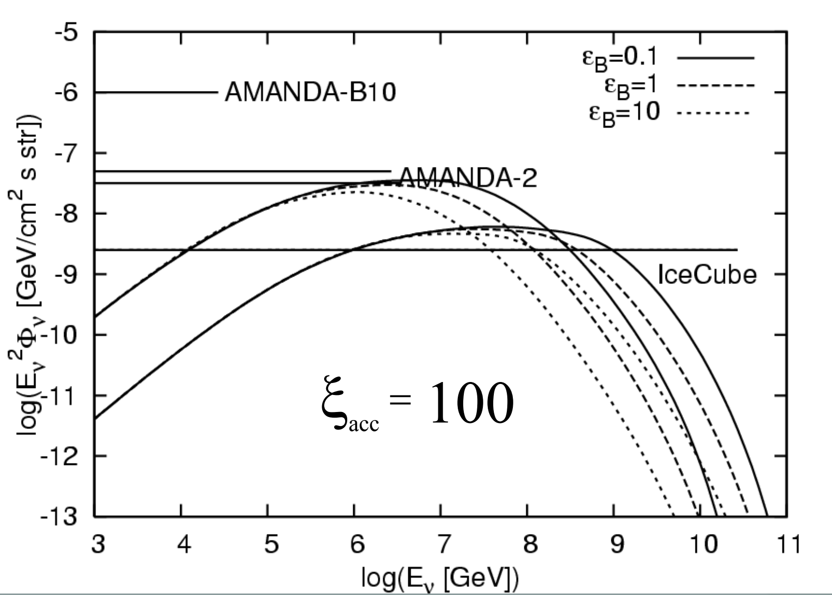
KM & Nagataki, PRD, 063002 (2006)

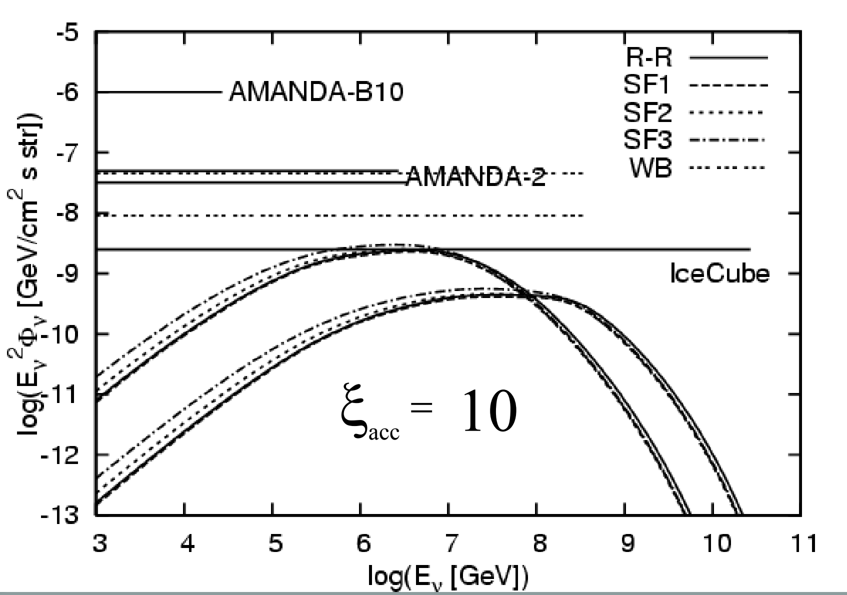
GRB Diffuse Neutrino Background

KM & Nagataki, PRD, 063002 (2006)

Assumption GRB rate ∝ star formation rate (Totani (1997))

"True" GRB rate $R_{GRB}(0) \sim (20-40)\ \mathrm{yr}^{-1}\ \mathrm{Gpc}^{-3}$ (Guetta et al. (2005))





- The case where typical collision radii are relatively small (<10^14cm)

  ξ acc ~10 → ~20 events/year (IceCube), GRBs are not main sources of UHECRs

  ξ acc ~100 → Higher neutrino flux than previous works.
- The case where typical collision radii are relatively large (>10^14cm)

  ξ acc ~100 (~ GRBs are the UHECR-origin) → ~20 events/year (IceCube)

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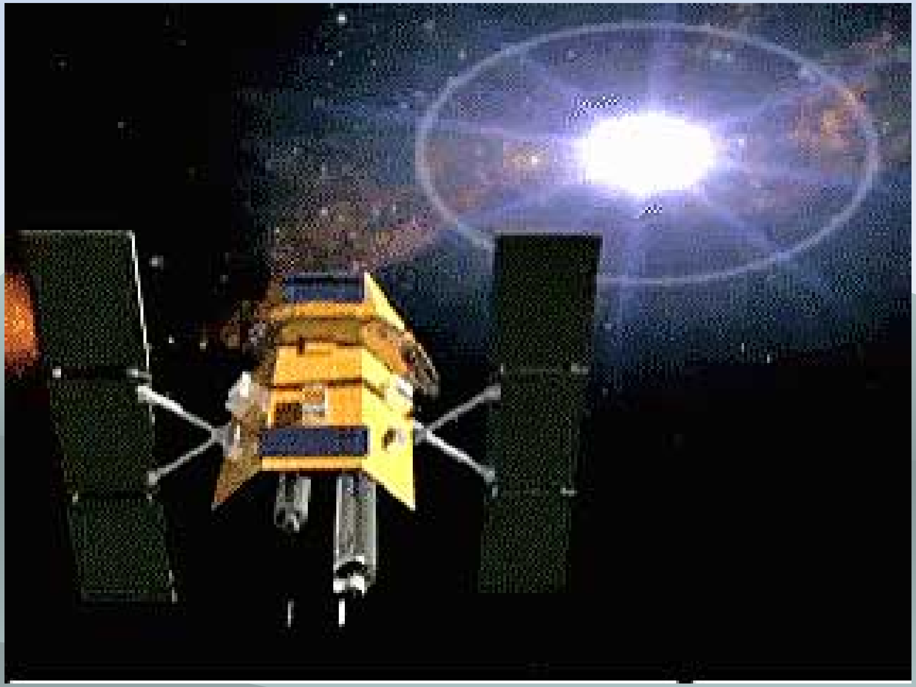
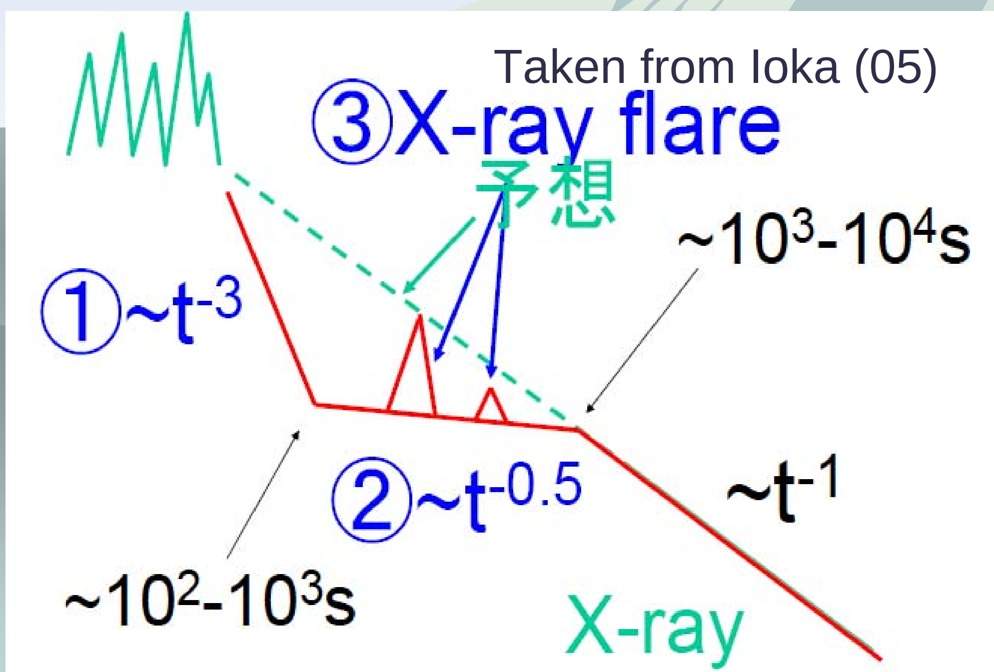
High Energy Neutrino Flashes from Flares in GRBs

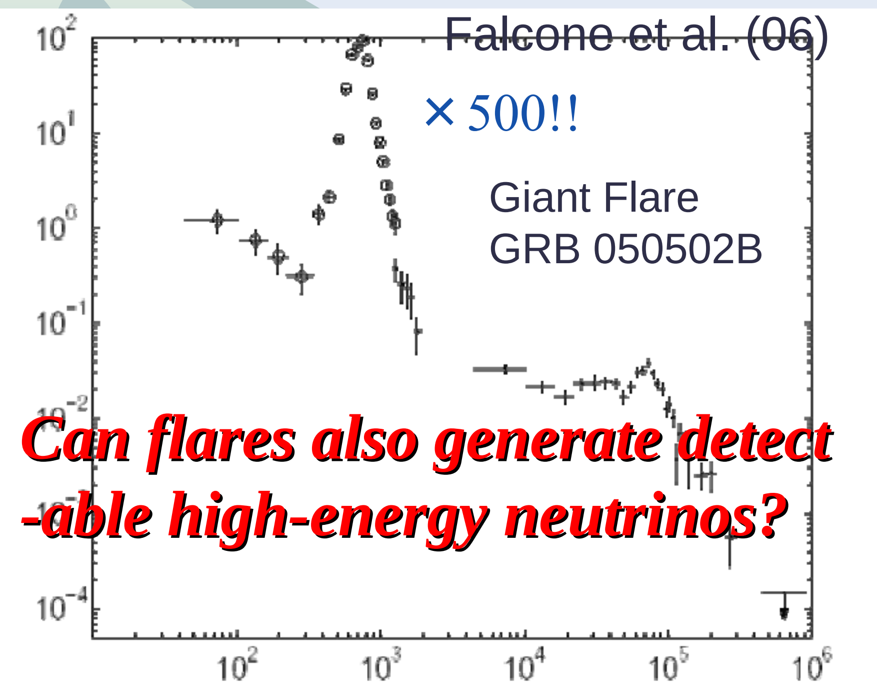


Surprises for Early Afterglow Emission

The Swift satellite gave us surprises!

1. **The steep decay ← high latitude emission** (Kumar & Panaitescu 00, Yamazaki et al. 05)
2. **The shallow decay ← a. energy injection?** (Sari & Meszaros 00) **b. time-dependent microscopic parameters?** (Ioka et al. 05) **c. two-components or subjets model etc.?** (Granot et al. 06, Toma et al. 06)
3. **X-ray Flares → Implications for the late time activity** (Ioka et al. 05)





Can flares also generate detect-able high-energy neutrinos?

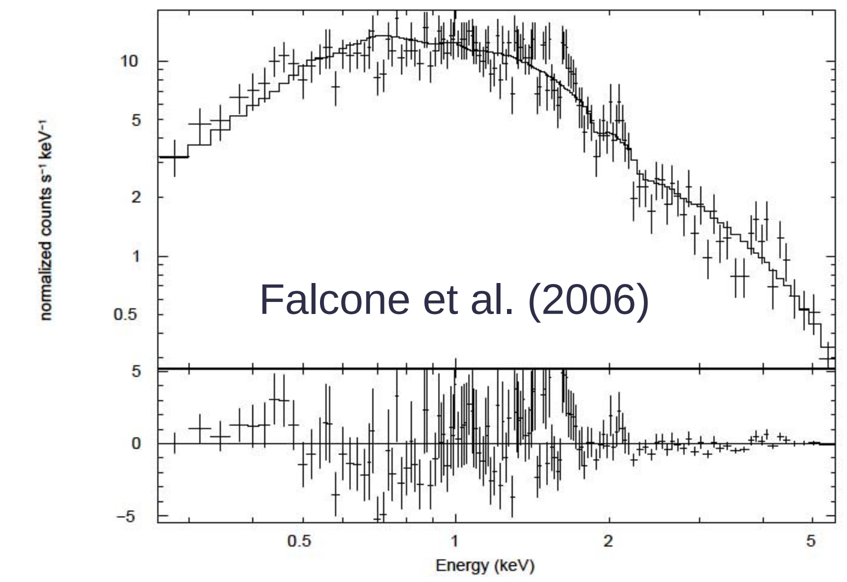
FUV/X-ray Flares

The origin of Flares is an open problem

Some have multiple flares.

Energy of flares can be comparable to that of prompt emission.

- **Late internal shocks** (Fan et al. (05), Burrows et al. (05), Zhang et al. (05))
- **Magnetic origin** (Fan et al. (05), Proga & Zhang (06), Dai et al. (05))
- **Reverse shock Inverse Compton flare** (Kobayashi et al. (05))
- **Density bumps?/Refreshed shocks?/Two component jets?**



•We study neutrino emission under the ***late internal shock model***.

→ **The detection may test the origin of flares (baryonic or magnetic).**

•We take the photon spectral shape ***similar to*** that of prompt emission.

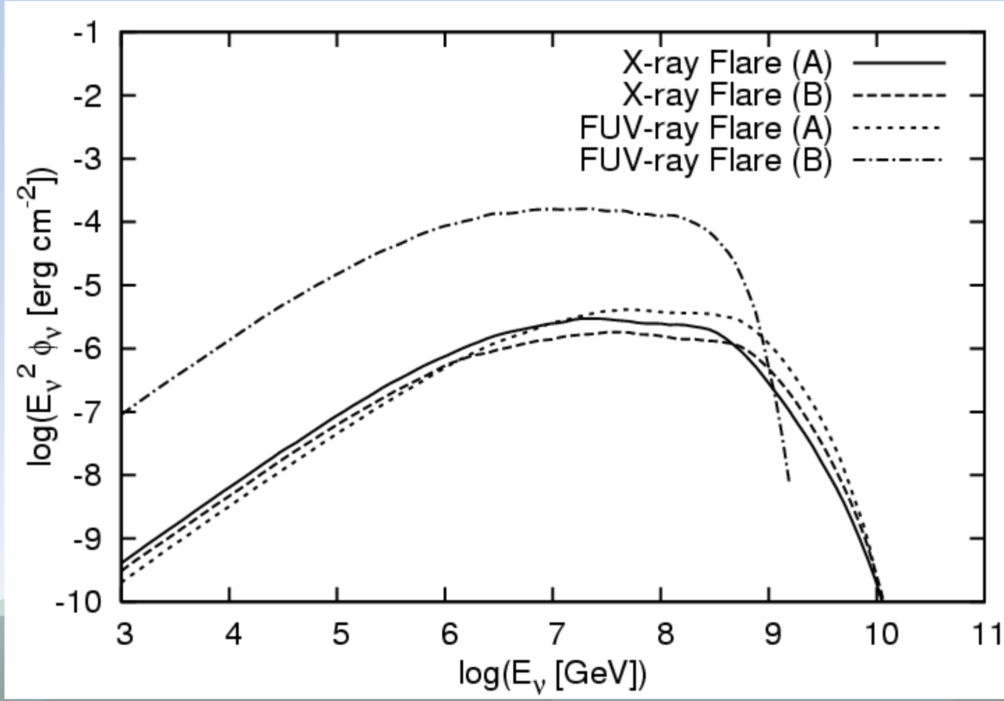
•We allow for the possibility of not only **X-ray flares (~1keV)** but also **far-ultraviolet flares (~0.1keV).** (Fan et al. (05))

Parameters we take

Isotropic luminosity	$L_{ph}^{iso} \sim (10^{47} - 10^{50})$ ergs/s
Variability time	$\delta t \sim (10 - 10^{3})$ s
Collision radii	$r \sim (10^{14.5} - 10^{16})$ cm
Number of collisions	$N \sim (1 - 10)$
Assume relatively low Lorentz factors (c.f. Falcone et al. 2006)	$\Gamma \sim (10 - 50)$

PeV-EeV Neutrino Flash from One z=0.1 Event

KM & Nagataki, PRL, 97, 051101

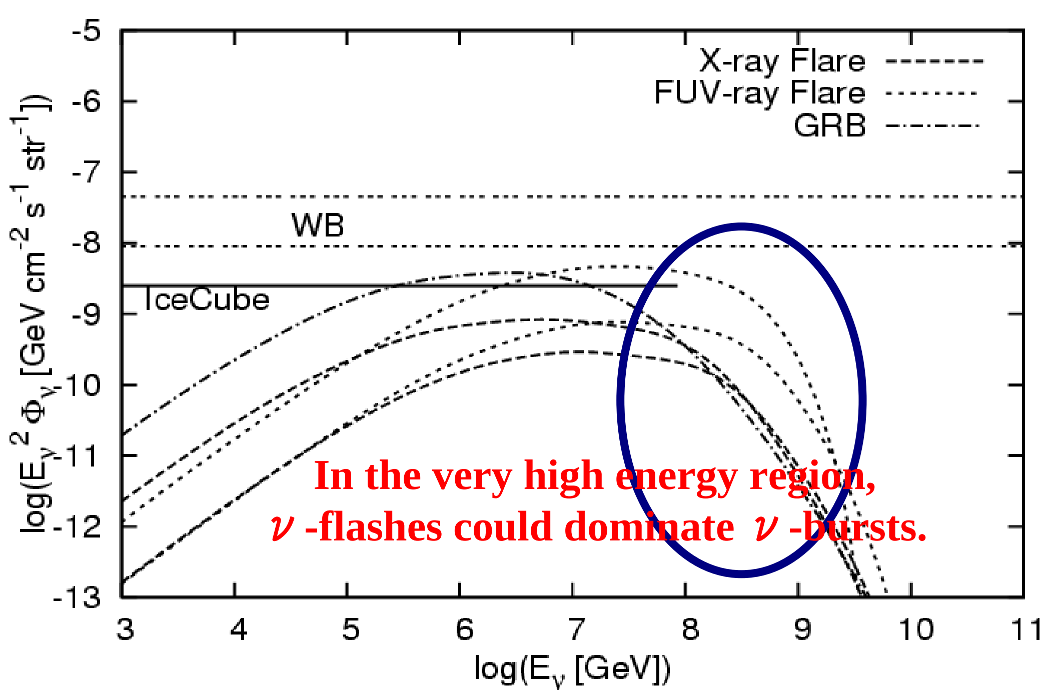


X (A): L=10^49 ergs/s, δ t~15 s, ξ acc=10
X (B): L=10^48 ergs/s, δ t~150 s, ξ acc=10
FUV (A): L=10^48 ergs/s, δ t~150 s, ξ acc=10
FUV (B): L=10^50 ergs/s, δ t~15 s, ξ acc=30

•Neutrino signals only from energetic and/or very near flares can be detected by IceCube. (Enough large baryon-loading is needed.)
•In such cases, we may detect delayed γ s by BAT and/or GLAST.
•FUV (B) is very energetic. Only when such an extreme flare occurs, we can detect ν s. (~1 event)
※In too copious photon field, highest ps suffer from the pγ reaction.

Neutrino Background from FUV/X-ray Flares

KM & Nagataki, PRL, 97, 051101

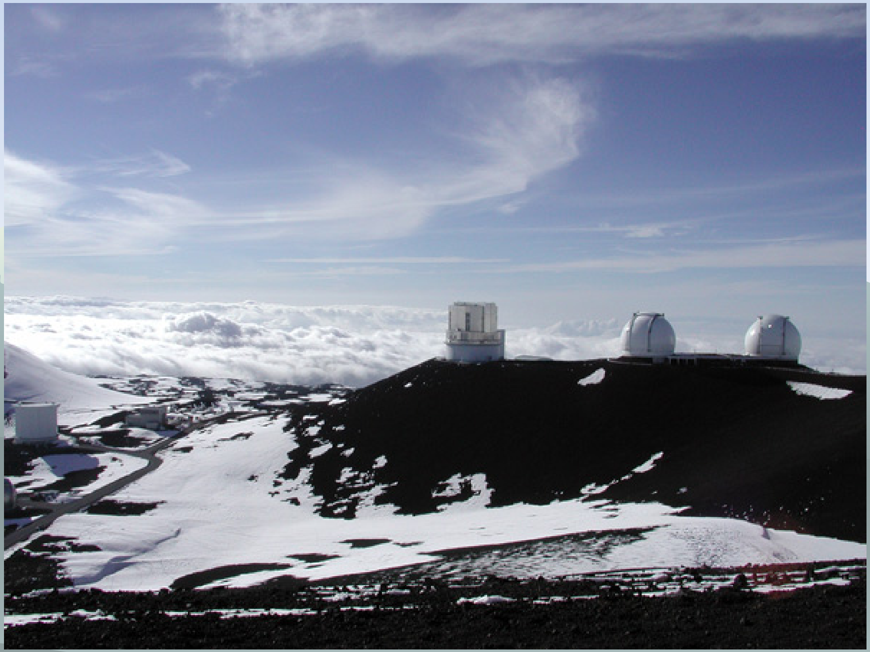


$$f \equiv \frac{E_{flares}}{E_{GRB}}$$

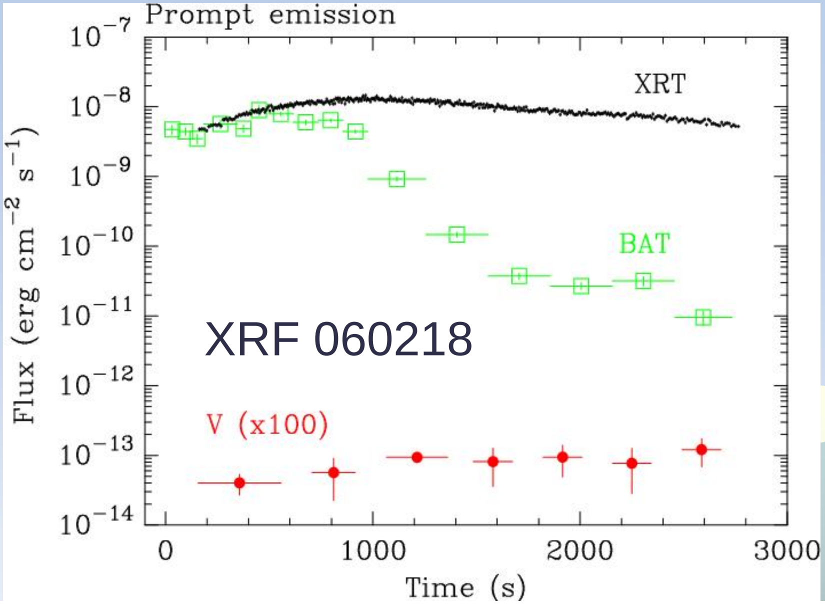
X (upper): L=10^49 ergs/s, δt~150 s, fξ acc=1, ξ B=1
X (lower): L=10^49 ergs/s, δt~15 s, fξ acc=0.5, ξ B=1
FUV (upper): L=10^49 ergs/s, δt~15 s, fξ acc=5, ξ B=0.1
FUV (lower): L=10^48 ergs/s, δt~150 s, fξ acc=1, ξ B=1

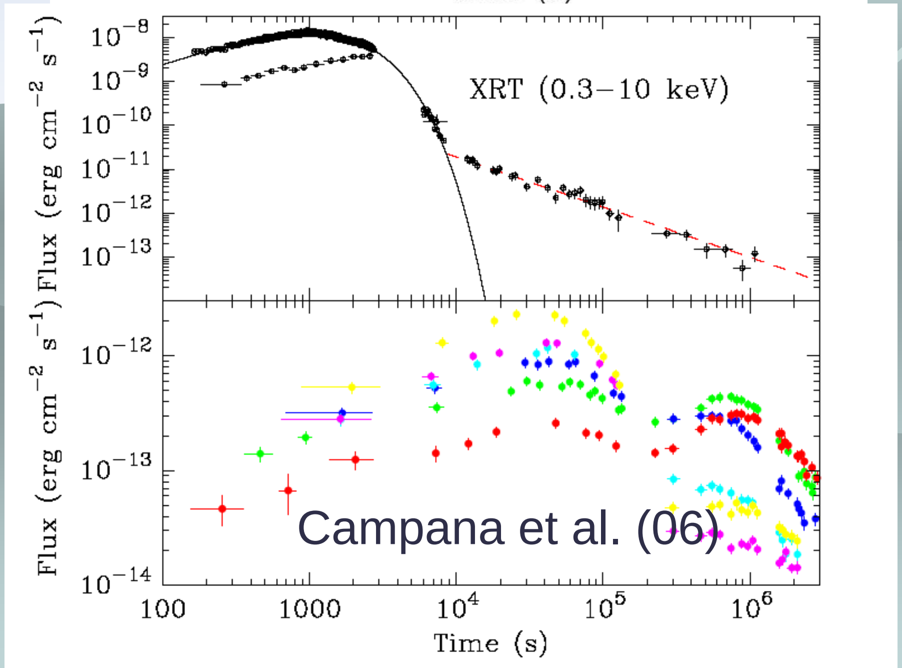
- **If *nonthermal proton energy ~ prompt γ-ray energy* (fξ acc~1), we can expect ~2 events/year (IceCube). ν -flash would be correlated with the early AG.**
- **For Γ ~ 10, pγ efficiency will be high** $(f_{p\gamma} \sim 1)$ **, and the source can be optically thick to pγ production in the very high energy region.**
- **The detection will be useful as the probe for natures of flares and physical parameters such as nonthermal energy, magnetic field, photon field.**

High Energy Neutrinos from Low-Luminosity GRBs



The Discovery of Nearby Event XRF 060218





XRF 060218

- Associated with SN 2006 aj (type IC)
- The second nearest GRB (~140 Mpc)
- The first GRB from which the thermal emission (~0.1 keV) was detected
  → shock break out?
  → cocoon emission?
- Very long burst (~1000s)
- **Lower-luminosity burst** (Liso~10^47 ergs/s)
- **Very large opening angle?** (θ ~1 rad)
- **Lower peak energy** (Epeak~5 keV)

Distinct population of GRBs?

Swift one-year operation ***suggests***…

$$\text{True Rate} \sim 230\ \text{yr}^{-1}\ \text{Gpc}^{-3}$$

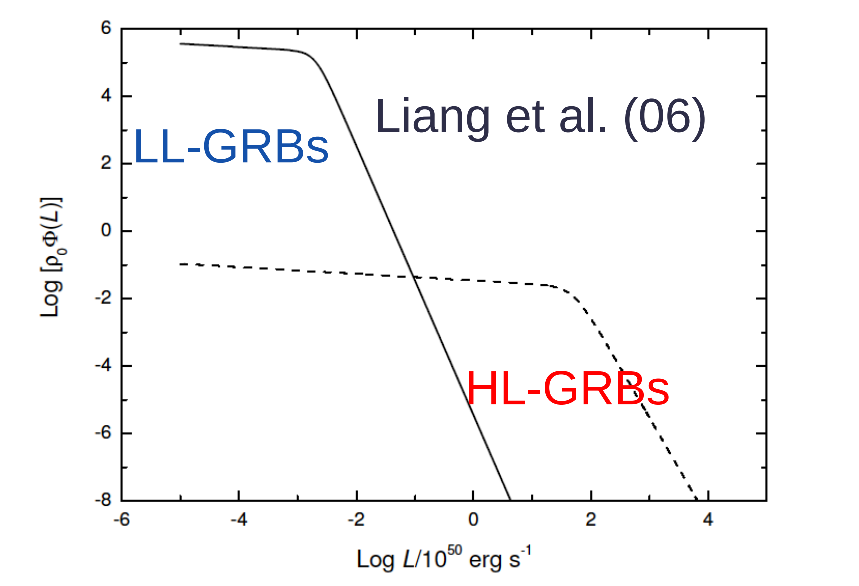
(Soderberg et al. (06))

Recent analysis using 3 nearby GRBs ***implies***…

$$\text{Apparent Rate} \sim 500\ \text{yr}^{-1}\ \text{Gpc}^{-3}$$

$$\sim 1\%\ \text{of SN Ibc Rate}$$

(Liang et al. (06))



Parameters we take

Isotropic luminosity	$L_{ph}^{iso} \sim (10^{45} - 10^{49})$ ergs/s
Variability time	$\delta t \sim (10^{2} - 10^{3})$ s
Collision radii	$r \sim (10^{14.5} - 10^{16.5})$ cm
Number of collisions	$N \sim (1 - 10)$
Lorentz factor	$\Gamma \sim (5 - 500)$

What is the origin of 060218-like low –luminosity (LL) bursts?
→Magnetar formation??
→Metallicity plays an important role?
→…

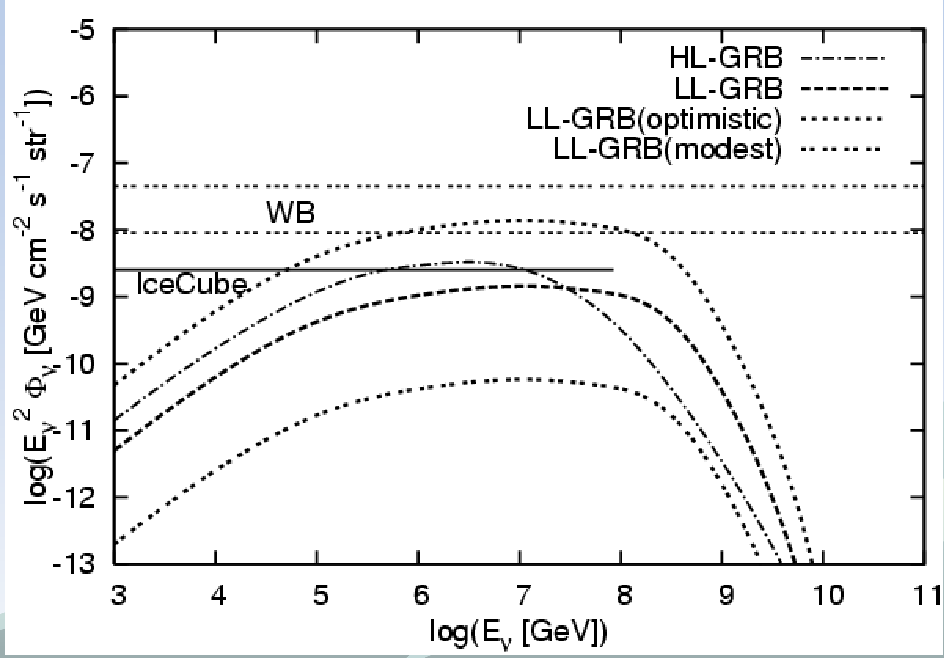
But most of LL-GRBs ***cannot be seen*** by Swift/BAT due to their low luminosity…

ν s will be useful for revealing them!!

Neutrino Background from LL-GRBs

KM, Ioka, Nagataki, & Nakamura, ApJL, submitted

(c.f. Gupta & Zhang (06))



ρ ≡ Apparent LLGRB Rate

Γ =10, L=10^47 ergs/s, δt~150 s, ξacc=10, ξB=1
LL-GRB: ρ =500 Gpc^-3 yr^-1
LL-GRB (optimistic): ρ =4800 Gpc^-3 yr^-1
LL-GRB (modest): ρ =20 Gpc^-3 yr^-1

- **Since the higher rate of LL-GRBs *could compensate* their lower released energy , we can expect ~10 events/year by IceCube.**
- **ν s are not correlated because most LL-GRBs cannot be detected by Swift/BAT. However, ν signals *might be able to indicate associated SNe* that could be detected by later optical follow-ups using Subaru, HST etc.**
- **These signals could be useful for revealing natures of LL-GRBs.**

※1 Only LL-GRBs with high Lorentz factor *could* explain observed UHECRs.

※2 Too high LL-GRB rate is *impossible* from radio observations of SNe Ibc.

(Soderberg et al . (06))

1. Introduction
2. High Energy Emission from GRBs
3. New Predictions in the Swift era
4. ***Galactic GRBs?***
5. Summary

GRBs in our Galaxy?

Possible GRB Remnants?

Whether there are galactic GRBs or not is ***very important*** because…

→ **UHECR-GRB connection** (ps with **~10^20 eV** can propagate **~10-100 Mpc**)

→ The possible probe of the unknown **jet structure**

→ GRBs could be one of **disasters for Life at Earth**.

Local true GRB rate implies…

→ **~ 10^-6 galaxy^-1 yr^-1** (HL-GRBs), **~ 10^-5 galaxy^-1 yr^-1** (LL-GRBs)

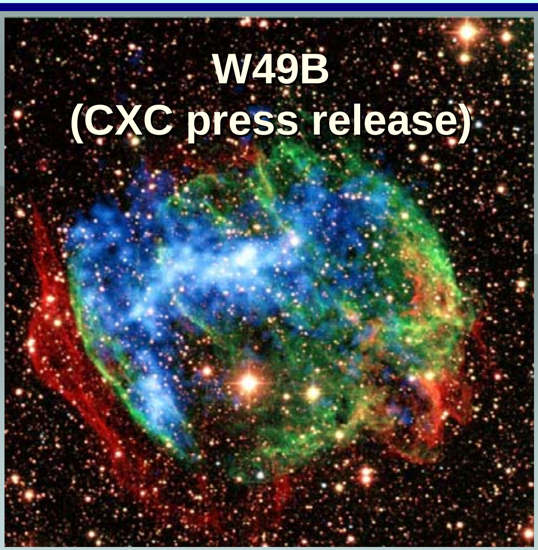
But these values are ***very uncertain***. So far, we have ***no*** direct evidences of GRBRs.

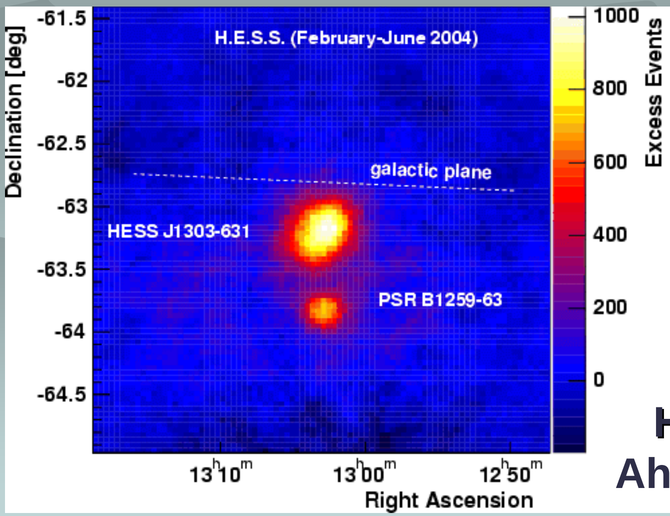
But there would be specific features for GRBRs...

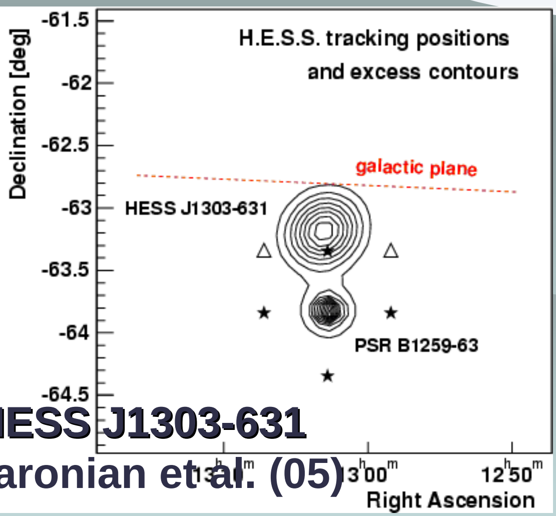
→**W49B** ・・ Fe and Ni lines, asymmetric bipolar explosion → jet? **(Ioka et al. (04))**

→**HESS J1303-631** ・・ NO <TeV Emission ← possible GRBR? **(Atoyan et al. (06))**

Existence of above GRBRs leads to the higher GRB rate **~10^-4 galaxy^-1 yr^-1**.







HESS J1303-631

Aharonian et al. (05)

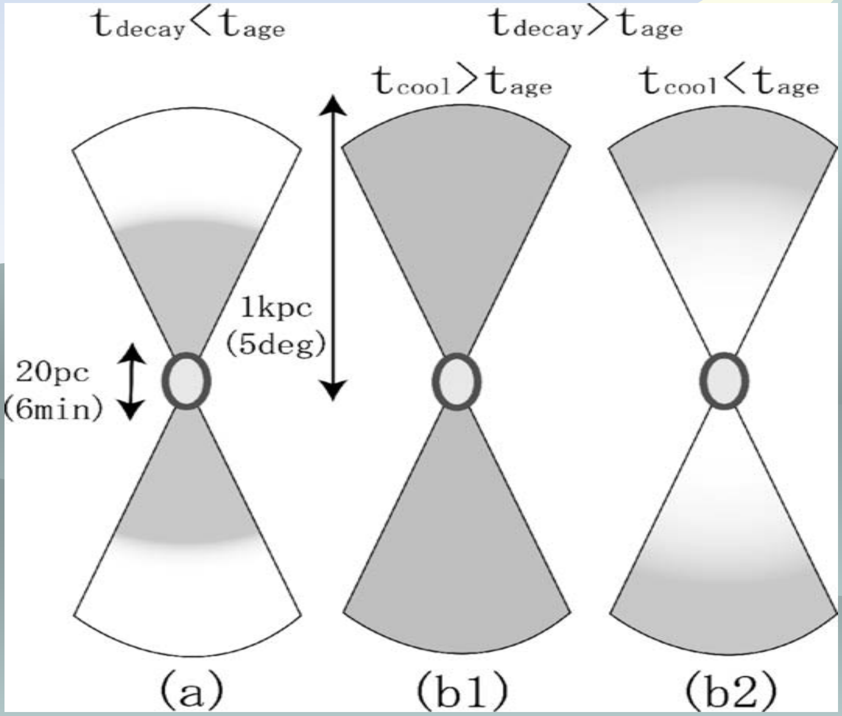
Supernova Remnant W49B

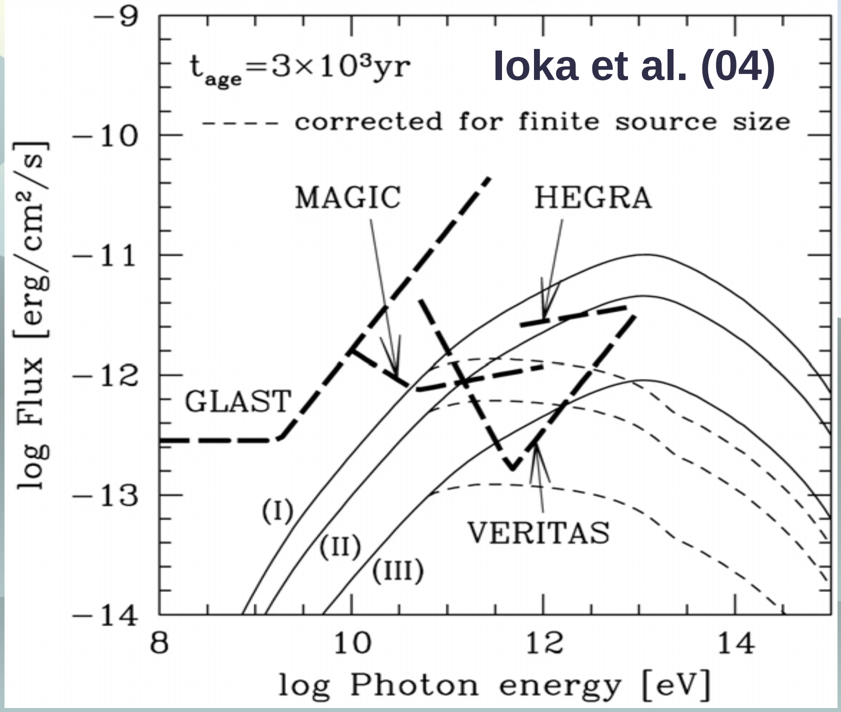
If W49B is a GRB remnant and **UHECRs come from GRBs…**

UHECR neutrons produced p γ reactions → **They will escape the ejecta**

Later neutron β decay → **Electrons radiate synchrotron emission (~100 eV) in galactic B and scatter off CMB photons (~50 TeV)** → **GeV-TeV emission!!**

※***Imaging permits distinguishing neutron-decay outside the source*** **from possible neutral pion-decay from protons accelerated at the SNR shock.**





However, the observed abundance pattern (Si, S, Ar) does not favor hypernova explosion. (Miceli et al. (06))

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Summary～高エネルギーガンマ線～

- シンクロトロン放射、逆コンプトン効果、パイオン起源の高エネルギーガンマ線をガンマ線バーストから期待できる。
  (あまりに高エネルギーな光子は電子陽電子対生成を起こしてソースからでられない可能性もある。)
- ソースから出た高エネルギーガンマ線は宇宙空間を伝播するうちにCMBやCIBと電子陽電子対生成を起こし、できたペアが主に逆コンプトンを起こすことで二次的な光子スペクトルもつくる。
- 二次的な光子スペクトルは銀河間磁場などの影響により、時間が遅れてやってくる。
- それらの高エネルギー放射をGLASTやMAGICなどで検出できる可能性がある。

- 天体の情報(光子密度、ローレンツ因子など)を知るための有用な手がかりの一つとなるだろう。
- 二次的な光子スペクトルから銀河間磁場の強度や不定性の多いCIBについてある程度制限を与えられる可能性がある。

Summary～高エネルギーニュートリノ～

- GRBの標準モデルにおけるニュートリノバースト、残光の今まででもっとも定量的に計算
  →**多重度/非弾性度**の考慮
  →**さまざまな冷却過程**を考慮
- Swift観測で示唆されるニュートリノ観測の可能性を新たに予言
  1. **フレアからのニュートリノフラッシュ**
  2. **光度の低いGRBからのニュートリノバースト**

- GRBに関する電磁波観測と独立な情報を与えうる
- バリオン加速の証拠、観測が進めば加速機構への貴重なアプローチとなりうる
- 最高エネルギー宇宙線起源の問題への重要な示唆

End…

<u>Thanks!</u>