Ultrahigh-Energy Photons as a Probe of the Highest-energy Cosmic Rays

～Transient Case～

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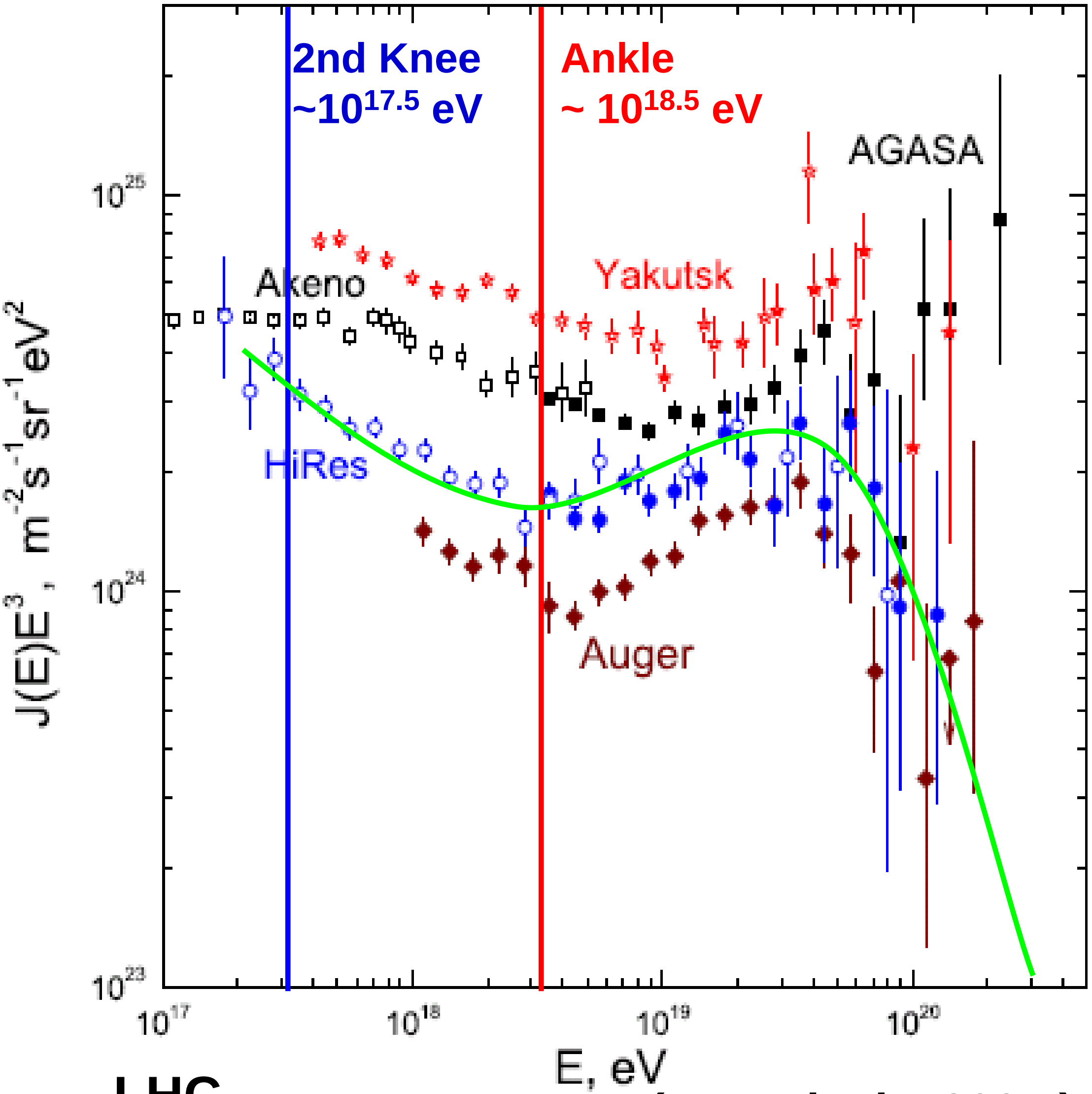
Ref: K. Murase, Phys. Rev. Lett., 103, 081102 (2009)
K. Murase & H. Takami, ApJL, 690, L14 (2009)

Ultrahigh Energy Cosmic-Ray Sources (UHECRs)



LHC

(Berezinsky 2007)

UHECRs

10^{20} eV ~ 20 J

not achieved by any accelerator on the Earth

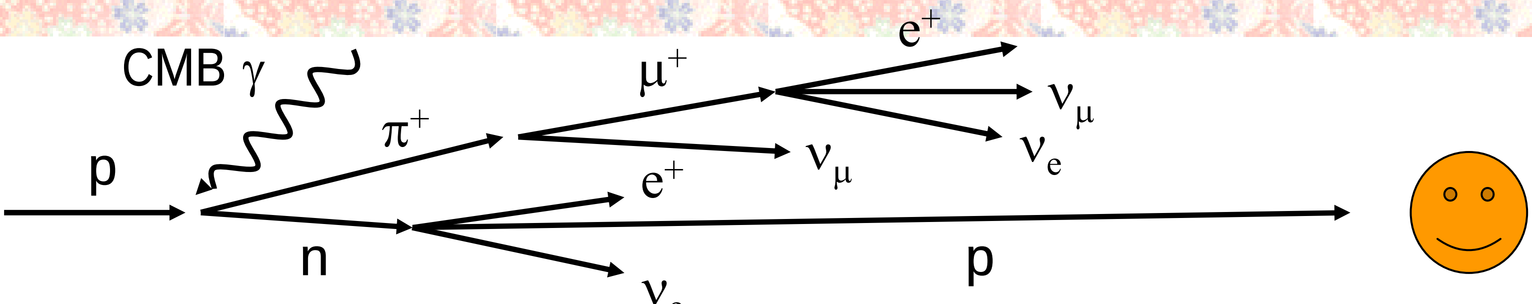
Information

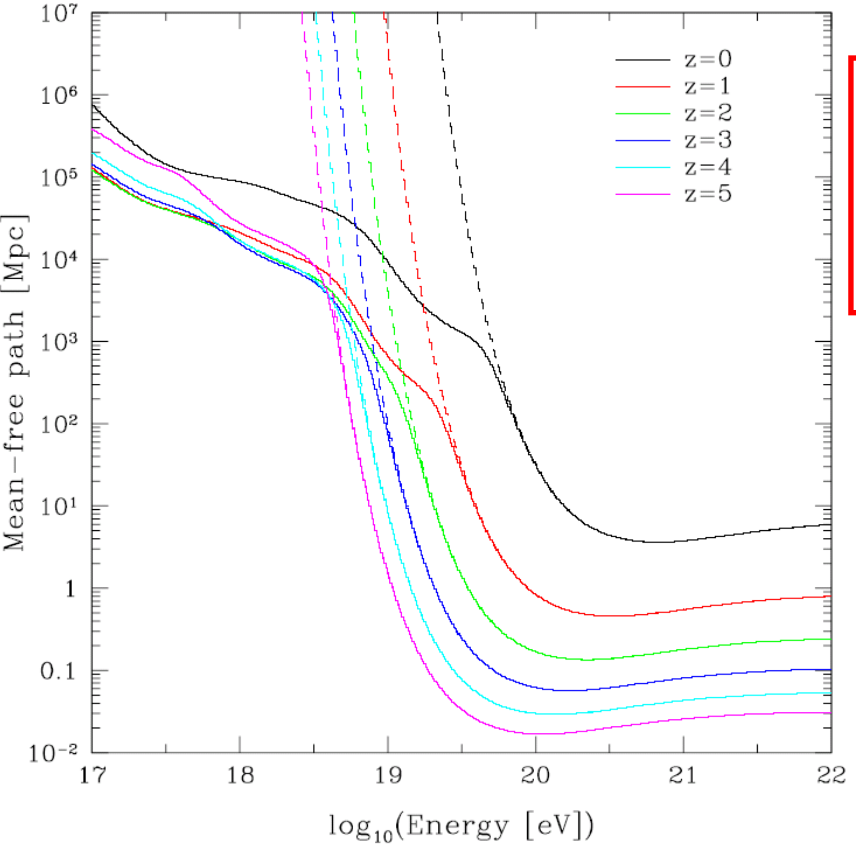
- **spectrum (e.g., ankle)**
- **composition**
- **arrival distribution**

Question

- **origin? （Extragalactic)**
- **generation mechanism?**

Greisen-Zatsepin-Kuzmin Mechanism





For protons with Ep>5×10^{19}eV
pγ reaction with CMB photons
→ energy loss length ~ 100 Mpc

Sources of observed UHECRs
→ nearby universe < 100 Mpc

Takami, KM, Nagataki, & Sato 2009, Astropart. Phys.

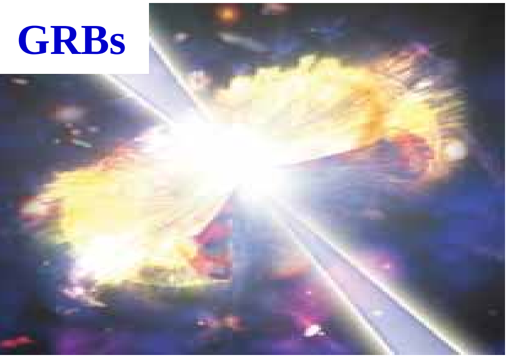
Candidates of the UHECR Origin

Necessary condition for UHECR acceleration (Hillas)

$E < ZeBr\beta$, $B^2/8\pi = L_B/4\pi r^2\Gamma^2\beta c$

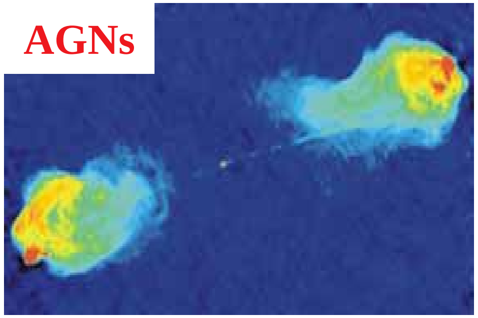
→ Necessary magnetic luminosity $L_B > 10^{45.5}$ erg/s $\Gamma^2 \beta^{-1} Z^{-2}$

GRBs



The most energetic explosion
$E_{GRB} \sim 10^{51}$ergs

AGNs



The most massive black hole
$M_{BH} \sim 10^{6\text{-}9} M_{sun}$

New Magnetars

The strongest magnetic field
$B \sim 10^{15}$ G

Clusters

The largest gravitational object
$r_{vir} \sim$ a few Mpc

Source Requirement & Persistent AGNs

- **Necessary condition for UHE proton acceleration (Hillas)**

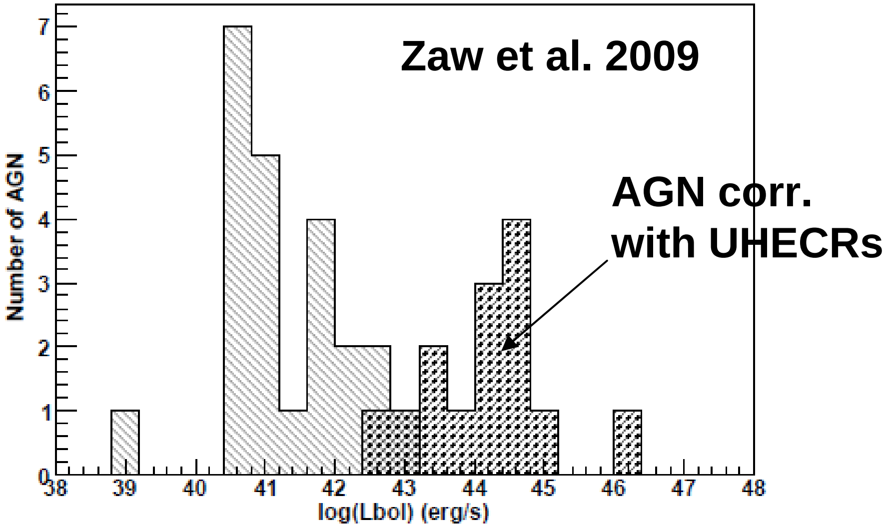
$E < eBr\beta$, $B^2/8\pi = L_B/4\pi r^2\Gamma^2\beta c$

→ Necessary magnetic luminosity $L_B > 10^{45.5}$ erg/s $\Gamma^2\ \beta^{-1}$

- **ActiveGalactic Nuclei (AGN)＝typical persistent candidates**

1. A small fraction of nearby AGNs satisfy $L_{jet} > 10^{45.5}$ erg/s
(e.g., FR II： $n_{FRII} \sim 10^{-(7\text{-}8)}$ Mpc^{-3} << Auger: $n \sim 10^{-4}$ Mpc^{-3})

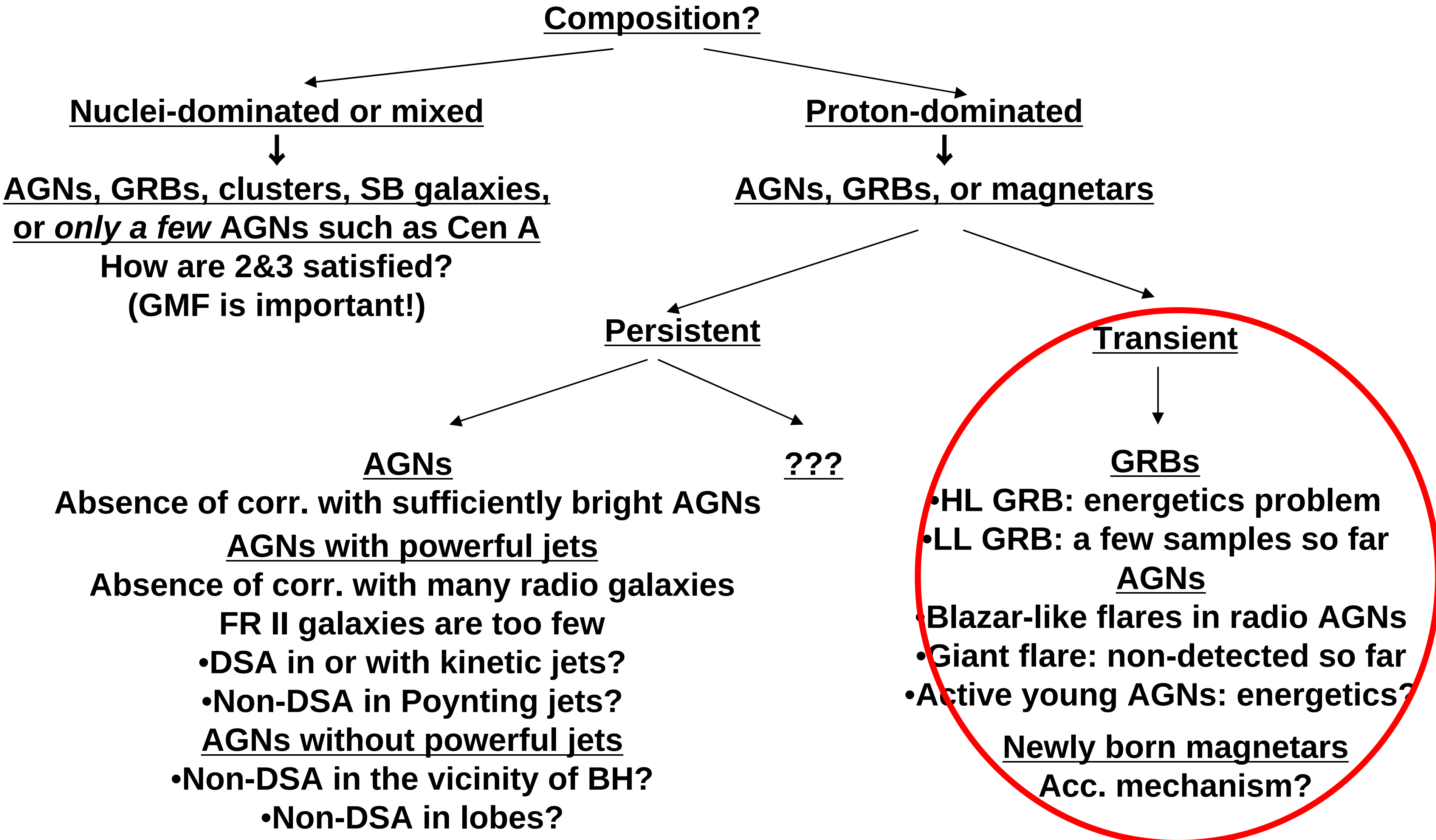
2. Correlated AGNs seem dim
($L_{bol} < 10^{45}$ erg/s)



→One of the solutions:
Transients (flares or bursts)

Another solution: heavy nuclei
e.g., radio-quiet AGNs (Peer, KM, & Meszaros 2009)

Information from UHECR observations (low statistics at present)
1. Spectrum (SD+FD) → GZK or non-GZK cutoff?
2. Anisotropy (above the GZK energy) → correlation with the sources?
3. Composition (Xmax and its fluctuation) → p or Fe or mixed?



Composition?

Nuclei-dominated or mixed

AGNs, GRBs, clusters, SB galaxies,
or *only a few* AGNs such as Cen A
How are 2&3 satisfied?
(GMF is important!)

Proton-dominated

AGNs, GRBs, or magnetars

Persistent

AGNs
Absence of corr. with sufficiently bright AGNs
AGNs with powerful jets
Absence of corr. with many radio galaxies
FR II galaxies are too few
•DSA in or with kinetic jets?
•Non-DSA in Poynting jets?
AGNs without powerful jets
•Non-DSA in the vicinity of BH?
•Non-DSA in lobes?

???

Transient

GRBs
•HL GRB: energetics problem
•LL GRB: a few samples so far
AGNs
•Blazar-like flares in radio AGNs
•Giant flare: non-detected so far
•Active young AGNs: energetics?
Newly born magnetars
Acc. mechanism?

Strategy for Transient Sources

“Transients should be considered as a possibility”

- **What can we learn from UHECR obs.?** **(KM & Takami 2009, ApJL)**

→ Constraints on the energetics and local rate density

Requirements for UHECR Sources

Two requirements

- Accelerate CRs to (~10^{20} eV) without significant loss

  Hillas condition, detailed acceleration mechanisms

  photon and magnetic fields in the source

- Providing the sufficient amount of UHECRs

  If the sources are transient

  (UHECR energy budget ~ 10^{44} erg Mpc^{-3} yr^{-1})

  ＝(burst rate)×(UHECR energy input per burst)

  per volume

We show UHECR obs. partially solves the degeneracy

Constraints on Transient Sources

(apparent source density) = (apparent duration)×(burst rate)

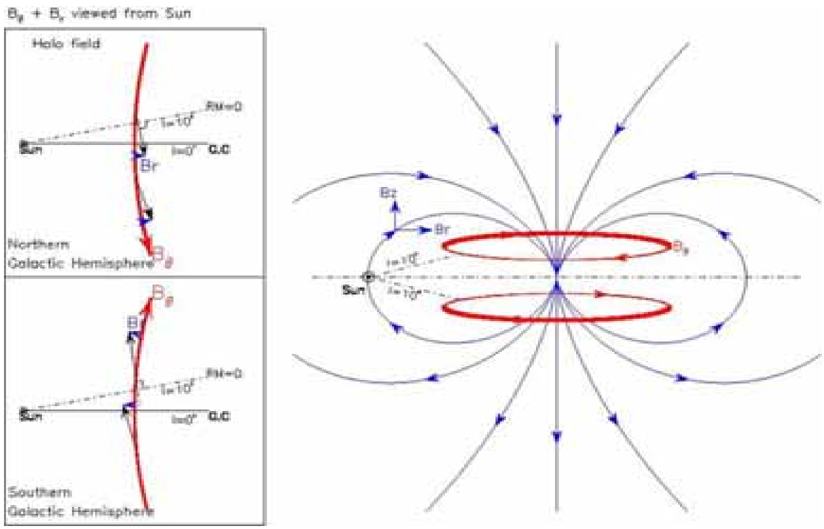
per volume

- **The apparent source density estimated from small-scale anisotropy**

  AGASA $n_s \sim 10^{-5}$ Mpc^{-3}, PAO: $n_s \sim 10^{-4}$ Mpc^{-3} **(e.g., Takami & Sato 08)**
- **Constraints on the apparent duration → constraints on the burst rate**

Points:

Apparent duration is determined by B



1. **GMF is unavoidable**

   (disk mag. $B_G \sim \mu$G

   + “possible” dipole halo mag.)

2. **IGMFs are especially unknown**

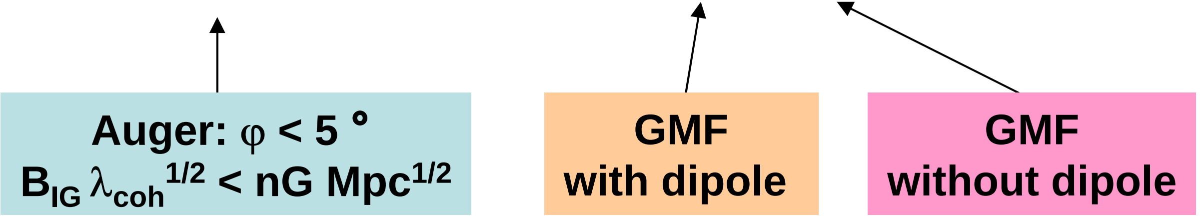
   But too strong GMFs and IGMFs lead to diminish positional correlation of $\varphi \sim$ a few ° suggested by PAO 2007

- Calculations of UHECRs propagating in the universe including both the GMF and IGMF (and relevant losses are considered)

(Yoshiguchi+ 03, Takami & Sato 07)

→ Constraints on the rate of bursts contributing the UHECR flux from PAO results **KM & Takami, ApJL, 690, L14 (2009)**

$$0.1\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1} \lesssim \rho_0 \lesssim (60\text{–}3000)\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}.$$



Auger: $\varphi < 5°$
$B_{IG}\,\lambda_{coh}^{1/2} <$ nG Mpc$^{1/2}$

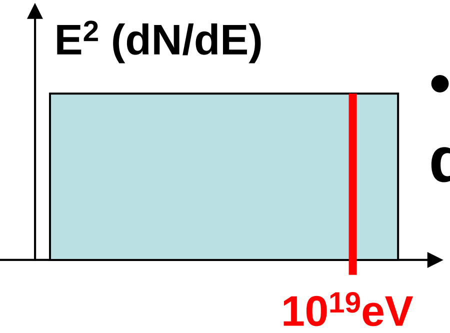
GMF with dipole

GMF without dipole

- Fits with the obs. spectrum → UHECR energy budget

→UHECR energy input per burst and the local burst rate can be determined at the same time

$$(0.3\text{–}20) \times 10^{50}\ \mathrm{erg} \lesssim \tilde{\mathcal{E}}^{\mathrm{iso}}_{\mathrm{HECR}} \lesssim 10^{54}\ \mathrm{erg}.$$ **at 10^{19} eV**



•Total CR energy E_{CR} would be much larger $dN/dE \propto E^{-2}$ implies $E_{CR} \sim \ln(10^{12}\mathrm{GeV/GeV})E_{HECR}$

$$10^{51}\ \mathrm{ergs} \lesssim \mathcal{E}^{\mathrm{iso}}_{\mathrm{CR}} \lesssim 10^{55.5}\ \mathrm{ergs}$$

Implications for Transient UHECR Sources

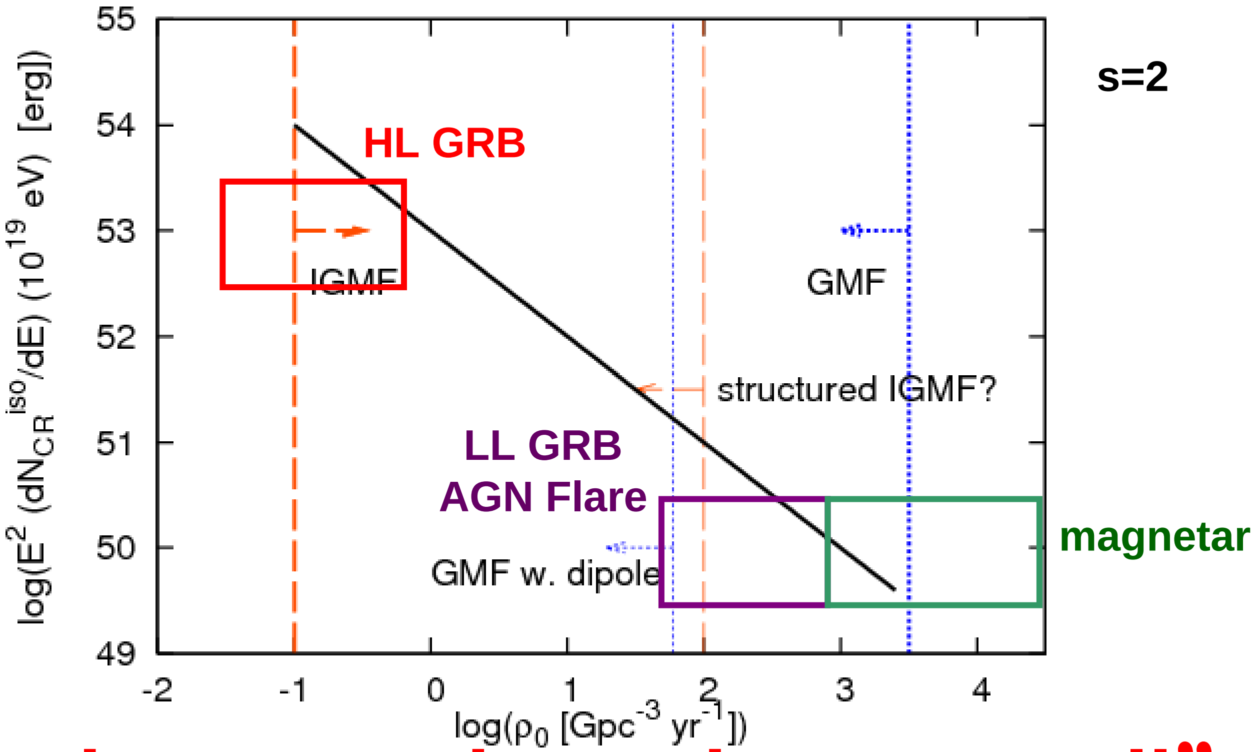
KM & Takami, ApJL, 690, L14 (2009)

High Luminosity GRB
Classical long GRBs
(Waxman 95, Vietri 95)

Low Luminosity GRB
Numerous but dimmer GRBs
(KM, Ioka, Nagataki, & Nakamura 06

Magnetar
Newly born (~ms) magnetars
(Arons 03)

Giant AGN Flare
>~ day flares per 10^{4-5} yr
(Farrar & Gruzinov 08)



"UHECR energy input per burst is not small"

Structured mag. ~Mpc w. 3 nG → < 100 $\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$

(Takami & KM, in prep.)

Strategy for Transient Sources

"Transients should be considered as a possibility"

- **What can we learn from UHECR obs.?** (KM & Takami 2009, ApJL)

  → Constraints on the energetics and local rate density
- **But… identifying the sources are difficult for transients**

  → MFs lead to UHECR delay time of >~100-1000 yrs

  (GMF and MF in the vicinity of the source are sufficient)

- **Neutrinos and γ rays from the source are more important**

$$p+\gamma \rightarrow \pi^{\pm},\pi^{0}+X \qquad p+p \rightarrow \pi^{\pm},\pi^{0}+X$$

$$\pi^{\pm} \rightarrow \mu^{\pm}+\nu_{\mu}(\overline{\nu}_{\mu}) \rightarrow e^{\pm}+\nu_{e}(\overline{\nu}_{e})+\nu_{\mu}+\overline{\nu}_{\mu} \qquad \pi^{0} \rightarrow 2\gamma$$

Calculation of High-Energy Emission

(e.g., KM 2007, PRD, 76, 123001; 2008, PRD(R), 78, 101302)

- **Input (we here consider GRBs and AGNs)**

  proton dis.: $N(\varepsilon_p) \propto \varepsilon_p^{-2} \exp(-\varepsilon/\varepsilon_p^{max})$,
  photon dis.: based on obs., magnetic field B: parameter

- **Meson production ($p\gamma$ and pp)**

  (based on exp. data, Geant4, and SIBYLL)
  ★multipion production is relevant for photon indices ≦ 1

- **Cooling processes: syn., IC, ad., BH, $p\gamma$, pp, (photodis.)**

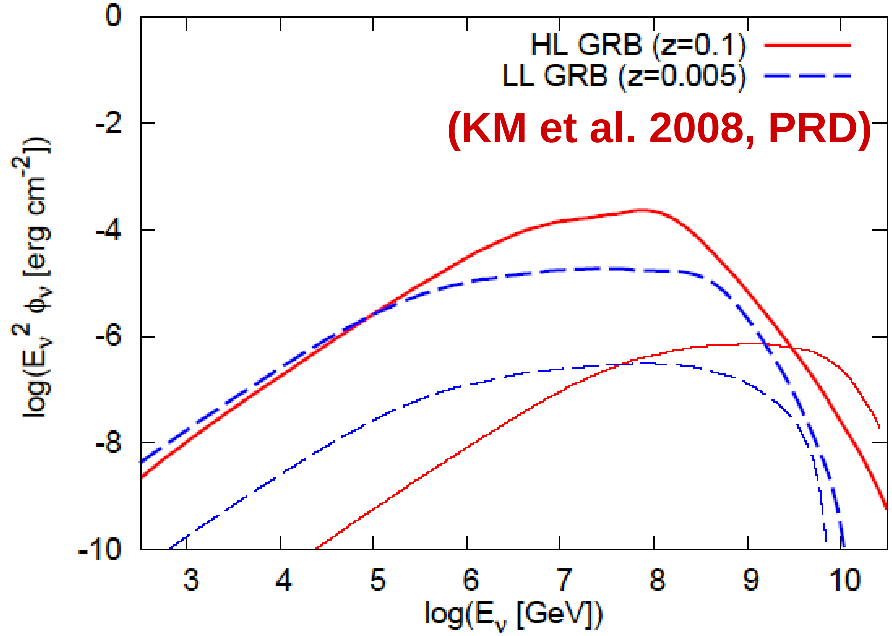
  ★maximum energy is determined by
  (acc. time ~ ε_p/eBc) < (cooling time), (dyn. time) + Hillas
  ★meson cooling is important when $t_{cool} < t_{decay}$

Here, we focus on γ rays that are not cascaded in the source
simple but sufficient for UHE γ rays in our typical cases

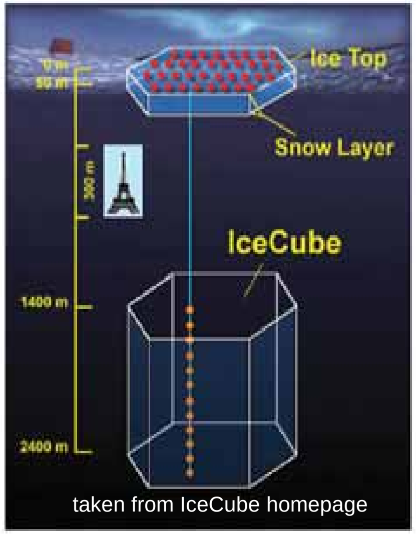
TeV-EeV Neutrinos

Neutrinos ⇔ a good probe of proton acceleration

TeV-EeV neutrinos may be detected by IceCube/KM3Net



(KM et al. 2008, PRD)



taken from IceCube homepage

- **Ex: prompt emission of high- and low-luminous GRBs**

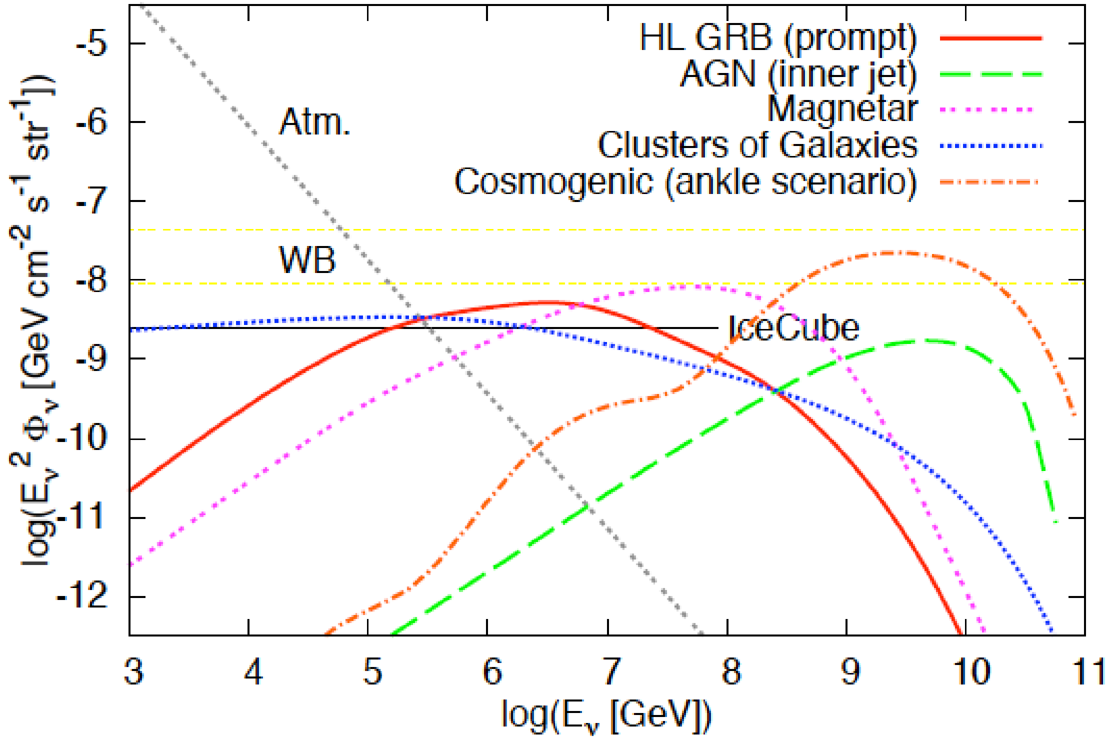
HL GRB: ~1 events @ z=0.1, LL GRB: ~0.2 events @ z=0.005

- Other possibilities (flares, afterglows...) **(KM 2007, PRD)**

The Cumulative Neutrino Background

Transients → space and time coincidence → atm. bkg. reduced

Testing some of the predictions is possible (but not easy for others)

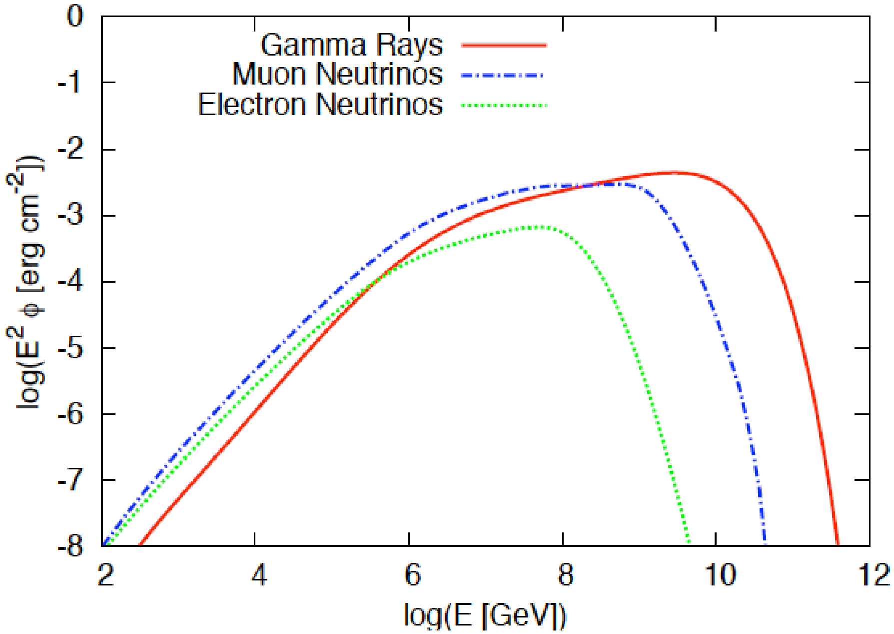


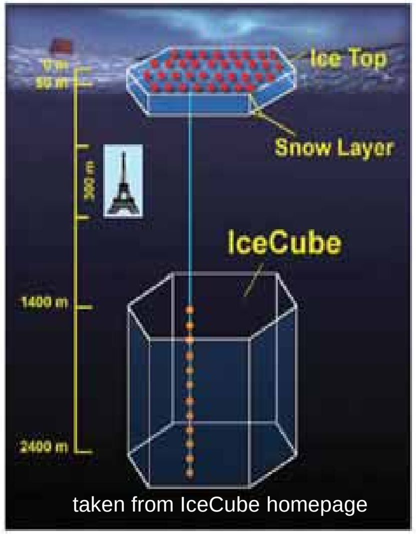
- **GRB prompt (Waxman & Bahcall 97, KM+ 06)、 early afterglow (e.g., KM 07)**
- **AGN jet (flare/non-flare), Cluster (non-flare) (e.g., KM et al. 08)**
- **Newly born fast rotating magnetar (KM, Meszaros, & Zhang 09)**

EeV Neutrinos?

Neutrinos ⇔ a good probe of proton acceleration

proof of UHECRs ⇔ Eν ~ 0.05Ep ~ 5 EeV (Ep/10^{20}eV)

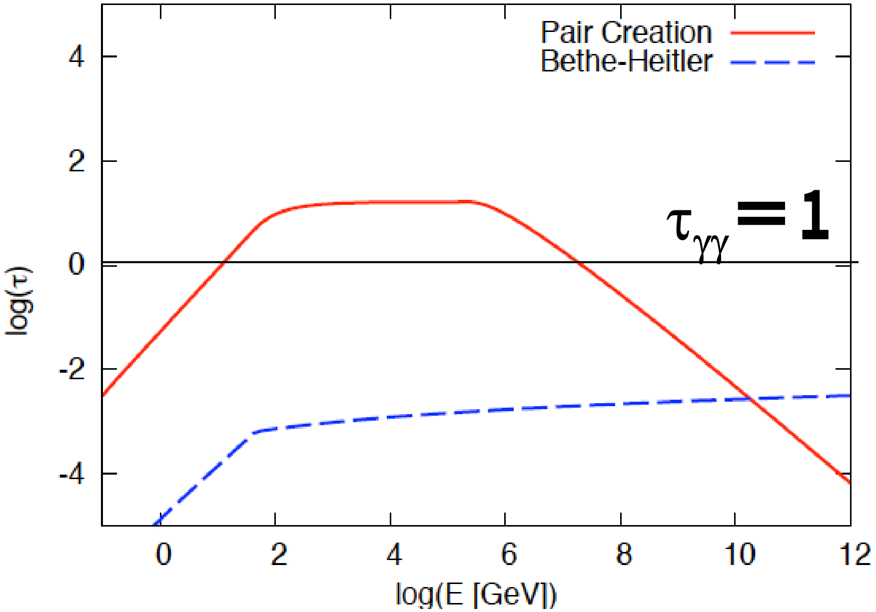


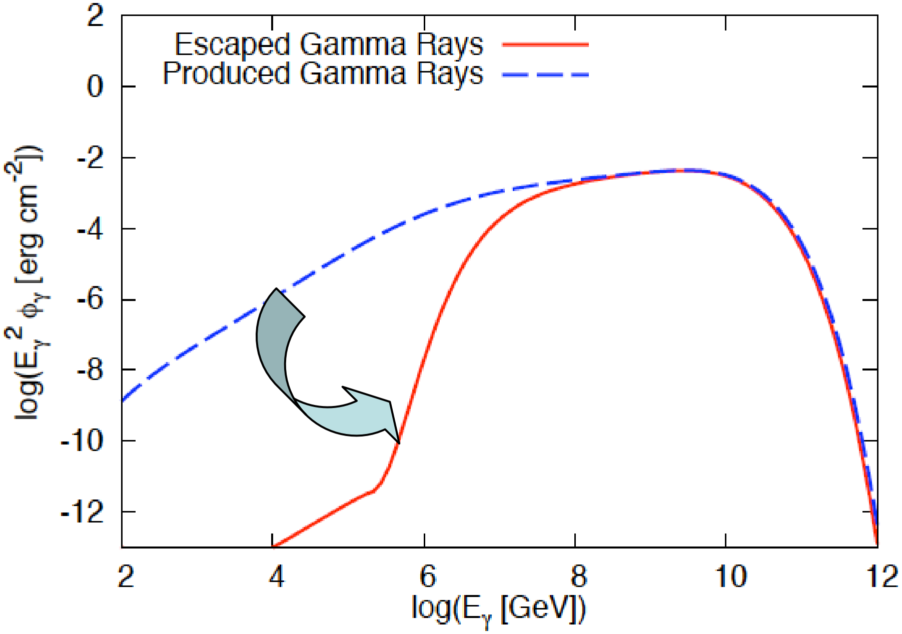


taken from IceCube homepage

- Syn. cooling of $\pi^{\pm}$ before decay → >EeV suppressed
- **IceCube (<100 PeV suitable); Auger (> EeV earth-skimming)**
- >EeV neutrino detections are not so easy…

Gamma Rays





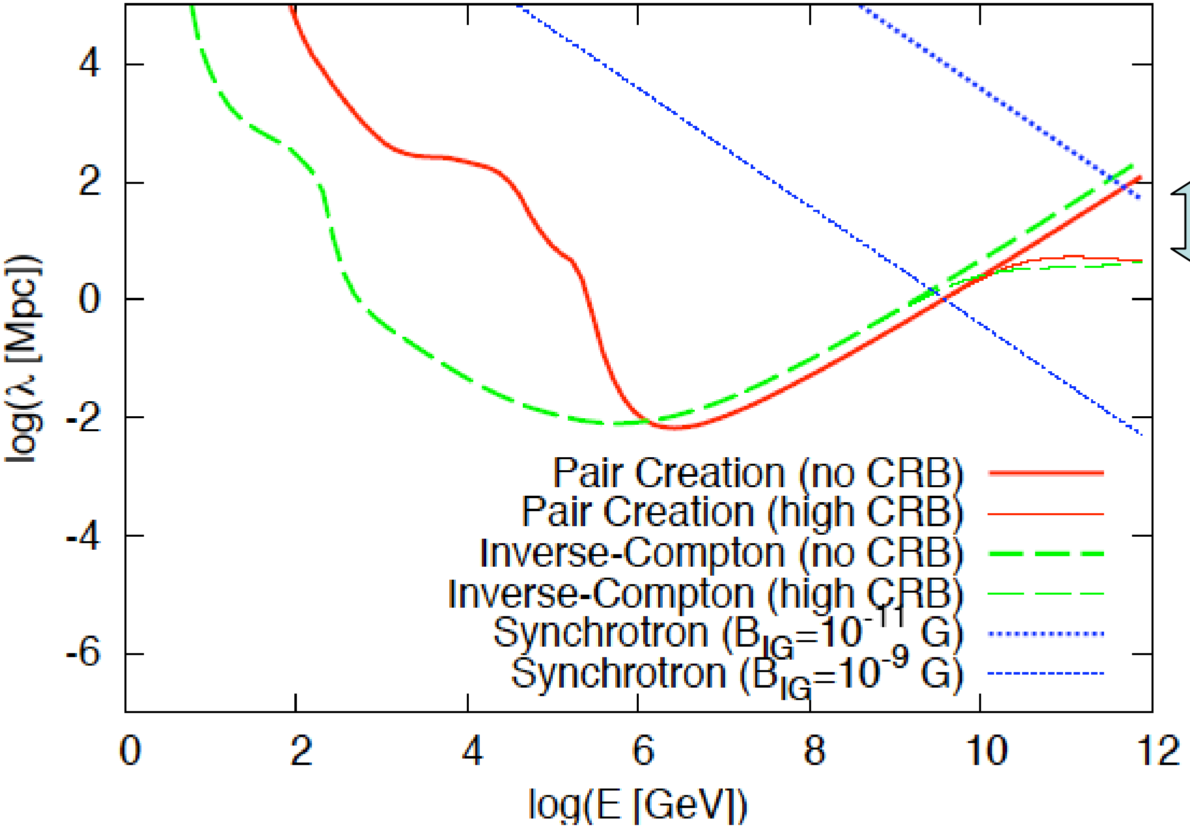
- **10 GeV-10 PeV γ rays cannot leave the source**
  →EM cascades in the source → GeV-TeV γ rays
  leptonic or lower-energy CRs can contribute

→ Talk by K. Asano

- **UHE γ rays can escape from the source**

Eγ ~ 0.1Ep ~ 10 EeV (Ep/10^{20}eV) ⇔ proof of UHECRs

Mean Free Path and Energy Loss Length



⇕ **uncertainty of the cosmic radio background (CRB)**

- 100 TeV-EeV γ rays ➞ λ << Mpc
- >10 EeV UHE γ rays ➞ λ > a few Mpc!

Electromagnetic Cascades

Cascades in the highest energies

Klein-Nishina (like) → leading particle effect

→ Approx. energy cons. in $\gamma \rightarrow e \rightarrow \gamma \rightarrow \cdots$ ($E_e \sim E_\gamma \neq E_\gamma/2$)

→ Eff. loss length is ~10 times longer (~10-100 Mpc)

- **EM cascades are treated in the rectilinear approx.
(valid when MF in voids is weak enough)**

$$\frac{\partial n_{e^-}(\gamma,t)}{\partial t} = Q(\gamma) + \frac{\partial}{\partial \gamma}\left\{ n_{e^-}(\gamma,t)\left[P_S(\gamma) + P_C(\gamma,t)\right] \right\}$$

(same for e^+)

$$\frac{\partial n_{ph}(\varepsilon,t)}{\partial t} = \underset{\text{syn.}}{R_S(\varepsilon,t)} + \underset{\text{IC}}{R_C(\varepsilon,t)} - \underset{\text{pair-creation}}{R_P(\varepsilon,t)}$$

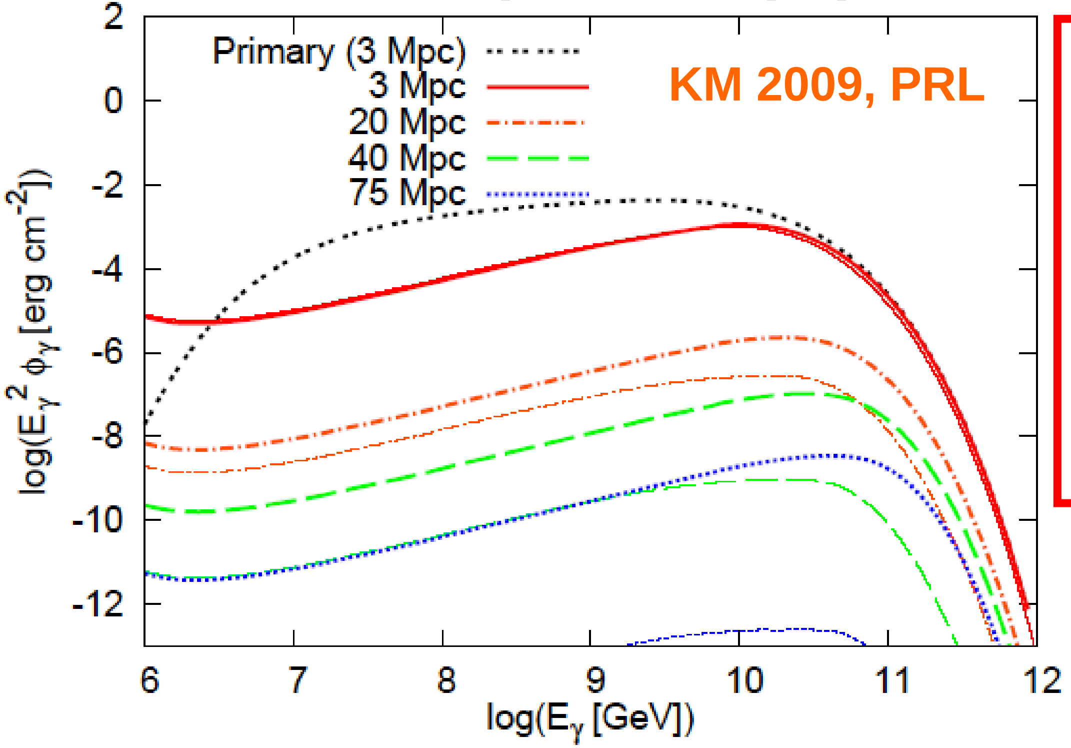
**(e.g., Bhatacharjee & Sigl 00,
see also Protheroe 86, Lee 98)**

Spectra of UHE Gamma Rays

Ex.: low-luminous (LL) GRBs (another ex.: AGN flares)

↑nearby GRBs were dim (980425@40Mpc, 060218@140Mpc)

∗Far LL GRBs (>>100 Mpc) cannot be seen by Swift/Fermi



KM 2009, PRL

somewhat bright LL GRB

$E_p^2\,(dN_{CR}/dE_p) \sim 10^{50.5}$ erg

$L_\gamma \sim 10^{48}$ erg/s, E_γ^b=10 keV

$U_\gamma = U_B$, $(U_p \sim 10 U_\gamma)$

$E_p^{max} \sim 10^{20.5}$ eV

$f_{p\gamma} = t_{dyn}/t_{p\gamma} \sim 0.03$

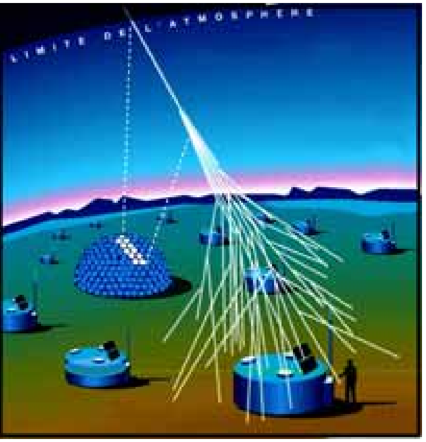
thick: no CRB
thin: extreme CRB

cascaded (<10 EeV), cascaded + non-cascaded (>10 EeV)

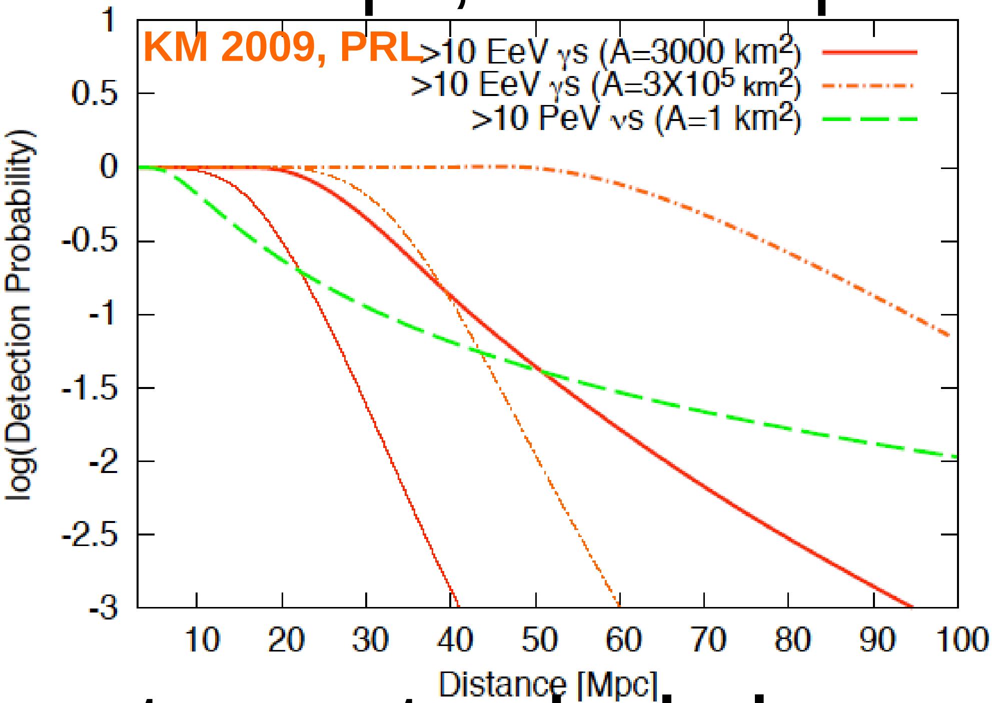
Detectability

$\sim10^{3.5}\mathrm{km}^2$：D <~40 Mpc; ~0.3-3 photons@20 Mpc

$\sim10^{5.5}\mathrm{km}^2$：D <~75 Mpc; ~0.3-30 photons@40 Mpc



Auger



JEM-EUSO

- **There is room to expect such a lucky event at < 100 Mpc**

General (KM & Takami 09): $10^{-3.5}$-10/yr, HL GRB (Waxman 95): 10^{-3}/yr

LL GRB (KM et al. 06), Giant AGN flare (Farrar & Gruzinov 09): 0.3-3/yr

Summary and Discussion

UHE γ: useful for identifying nearby UHECR sources

- **Especially important for transients (GRB, AGN) +all-sky monitor → time and space coincidence anisotropy in UHE γ-ray background (difficult)**
- **Useful even for persistent sources** (KM & Takami, in prep.) **(UHE γ rays produced during UHECR propagation)**
- **GeV-TeV γ–ray echoes/haloes can be important**

Bonus if UHE γ rays from the source are detected

- **Clues to the radio background and MF in voids**
- **>1000 times stronger constraints on the LIV**

Spares

On the Magnetic Fields

Q. UHECRs are delayed. How about UHE γ rays?
A. Cascaded UHE γ rays have much shorter delay time.

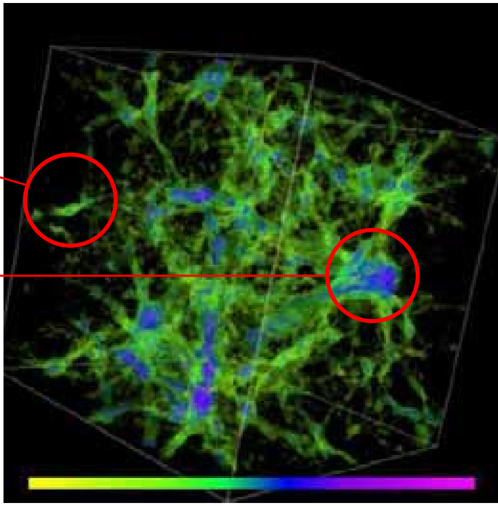
- **$10^{19.75}$ eV p delay time ~ $10^{2\text{-}3}$ yrs by the GMF (KM & Takami 09)**
- **$10^{19.75}$ eV p delay time > 100 yrs only by the structured MF**

Ex.: filaments w. B_{st}=1-3 nG, $\lambda_{st,coh}$=R=Mpc

→ p delay time ~ 100-1000 yrs

clusters w. B_{st}=0.1-0.3 μG, $\lambda_{st,coh}$=R=Mpc

→ p delay time ~ $10^{6\text{-}7}$ yrs



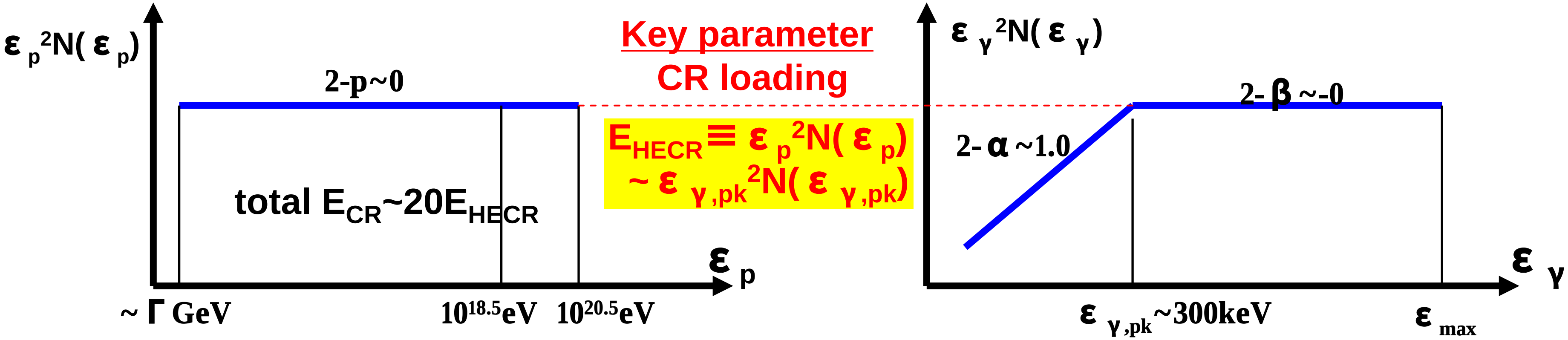
- **> 10^{19}eV UHE γ rays have $\lambda_{\gamma\gamma}$ > 3 Mpc**

They may feel only the weak void MF (< nG)

- **Void MFs can be very weak (even ~ 10^{-20} G is possible)**

B=10^{-13} G, λ_{coh}=kpc, D=50 Mpc → UHE γ delay time ~ 10^3 s

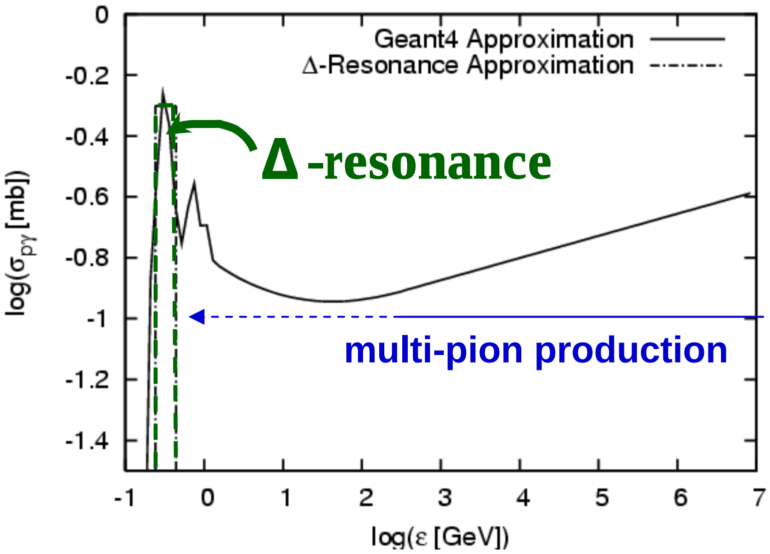
Example: GRB Neutrinos



Key parameter

CR loading

$E_{HECR} \equiv \varepsilon_p^2 N(\varepsilon_p) \sim \varepsilon_{\gamma,pk}^2 N(\varepsilon_{\gamma,pk})$



(in proton rest frame)

Photomeson Production

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

$$p + \gamma \rightarrow N\pi^\pm + X \quad \kappa_p \sim (0.4\text{—}0.7)$$

Δ-resonance approximation

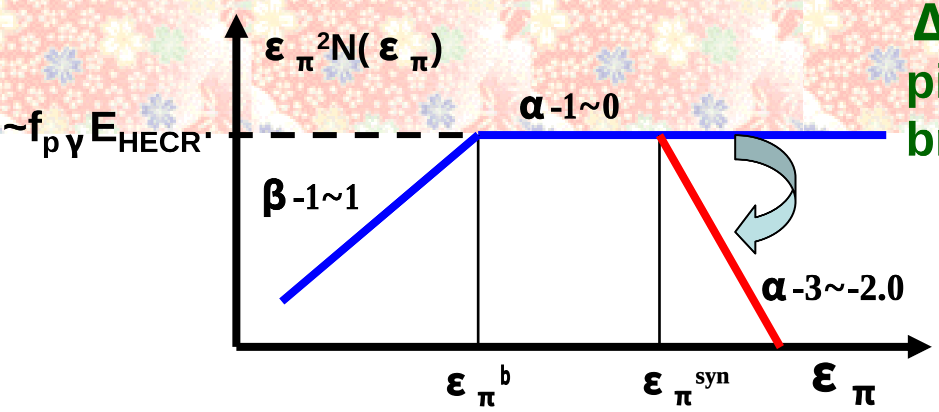
$\varepsilon_p \varepsilon_\gamma \sim 0.3\,\Gamma^2\,\mathrm{GeV}^2$

$\varepsilon_p^b \sim 0.3\,\Gamma^2/\varepsilon_{\gamma,pk} \sim 50\,\mathrm{PeV}$

Photomeson production efficiency
~ effective optical depth for pγ process

$f_{p\gamma} \sim 0.2\, n_\gamma \sigma_{p\gamma} (r/\Gamma)$

Meson Spectrum



Δ-resonance approximation

pion energy $\varepsilon_\pi \sim 0.2\ \varepsilon_p$

break energy $\varepsilon_\pi^b \sim 0.06\ \Gamma^2/\varepsilon_{\gamma,pk} \sim 10$ PeV

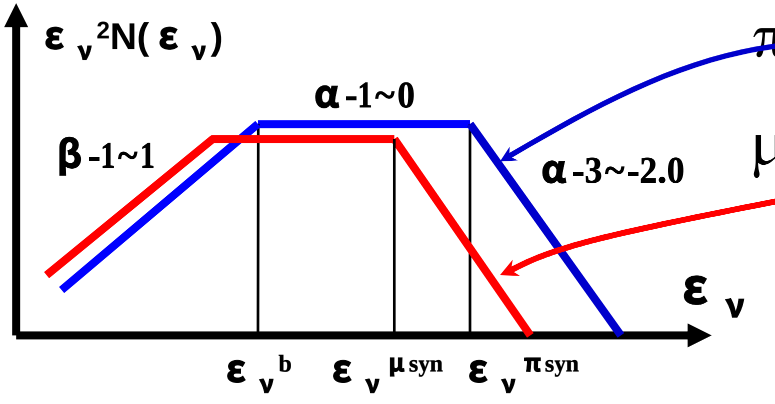
meson cooling before decay

(meson cooling time) ~ (meson life time)

→ break energy in neutrino spectra

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

Neutrino Spectrum



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

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

Δ-resonance approximation

neutrino energy $\varepsilon_\nu \sim 0.25\ \varepsilon_\pi \sim 0.05\ \varepsilon_p$

- **ν lower break energy $\varepsilon_\nu^b \sim 2.5$ PeV**
- **ν higher break energy $\varepsilon_\nu^{\pi syn} \sim 25$ PeV**

Neutrino oscillation

(Kashti & Waxman 05)

pγ process at Δ-res.

$$\nu_e : \nu_\mu : \nu_\tau = 1:2:0$$

$$\nu_e : \nu_\mu : \nu_\tau = 1:1:1$$

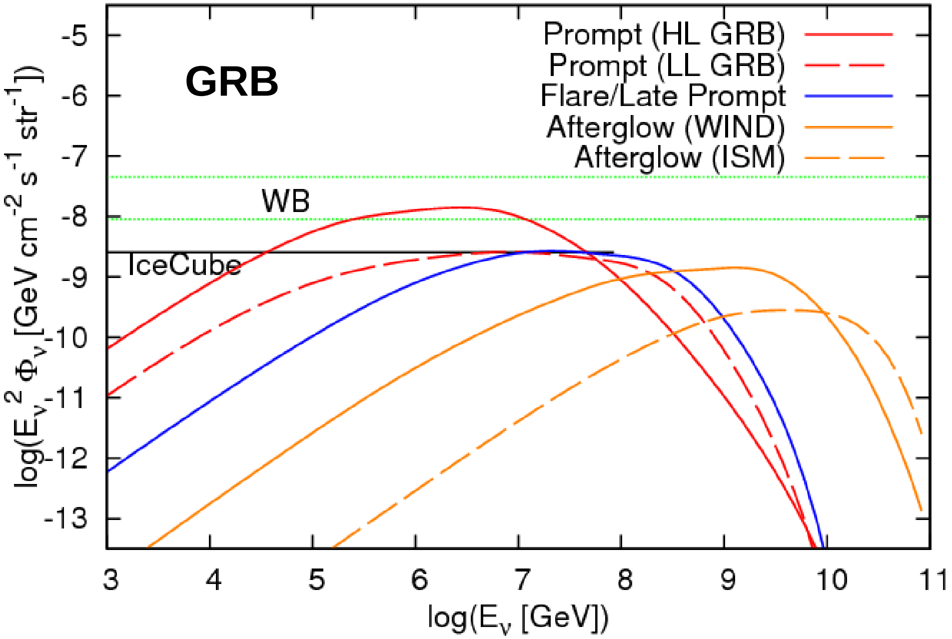
No loss

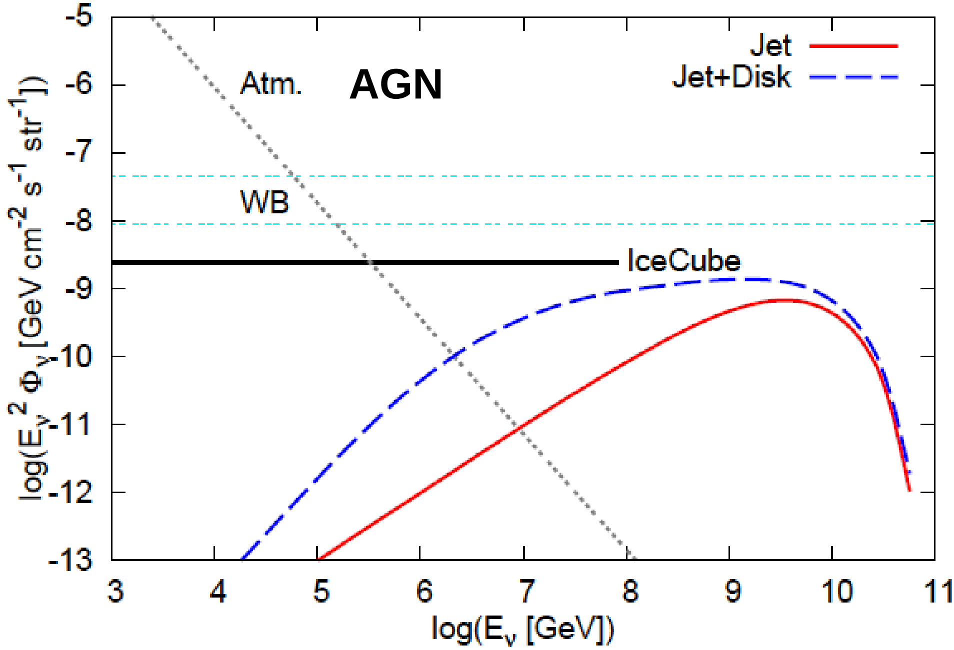
$$\nu_e : \nu_\mu : \nu_\tau = 1:1.8:1.8$$

High ε_ν Loss limit

Examples: GRBs and AGN Jets

KM & Nagataki, PRD, 73, 063002 (2006); KM, Ioka, Nagataki, & Nakamura ApJ, 651, L5 (2006); KM & Nagataki, PRL, 97, 051101 (2006); KM, PRD, 76, 123001 (2007) etc.





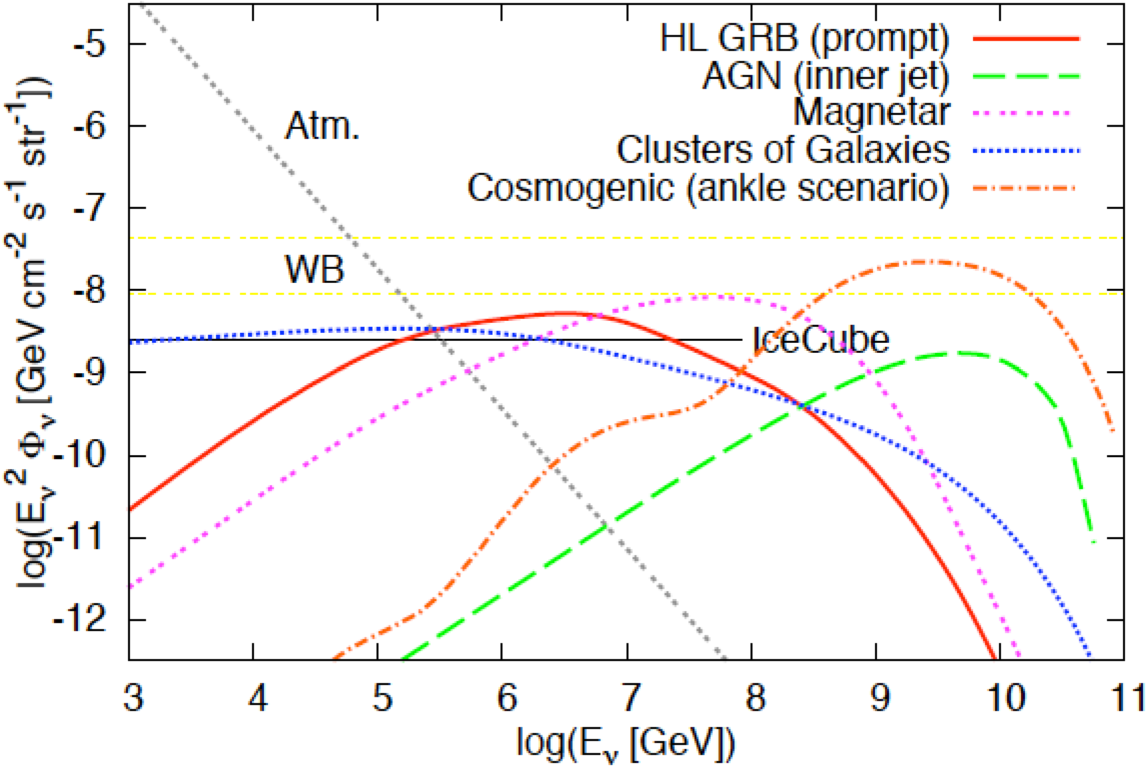
•Unique probe of baryon acceleration and source models

•IceCube, KM3Net → detection is possible especially for transients

•#~1-10/yr (optimistic), but #<1/yr (pessimistic) for 100TeV-100PeV

High-Energy Neutrinos

IceCube/KM3Net could detect the sources (especially if transient)



- GRB prompt **(Waxman & Bahcall 97, KM+ 06)**、 early afterglow **(e.g., KM 07)**
- AGN jet (flare/non-flare), Cluster (non-flare) **(e.g., KM et al. 08)**
- Newly born fast rotating magnetar **(KM, Meszaros, & Zhang 09)**