High-Energy Neutrinos as New Cosmic Messengers

Kohta Murase

Institute for Advanced Study, USA

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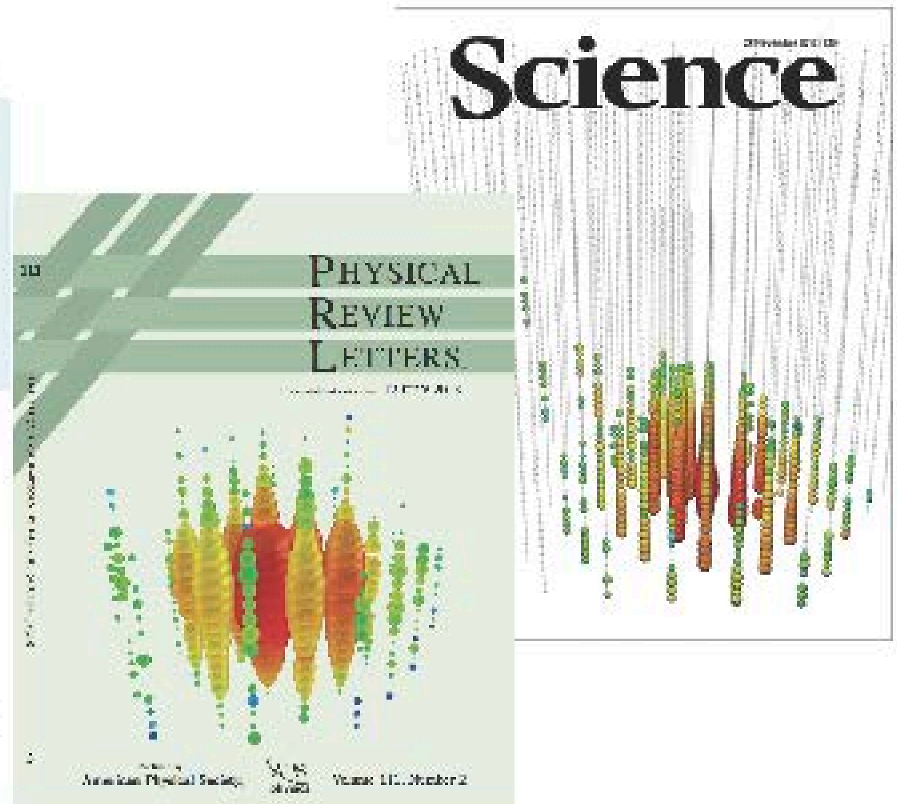
Outline

1. Introduction
2. Demystifying the origin of "diffuse" PeV neutrinos
3. GeV-PeV neutrinos as a probe of relativistic jets

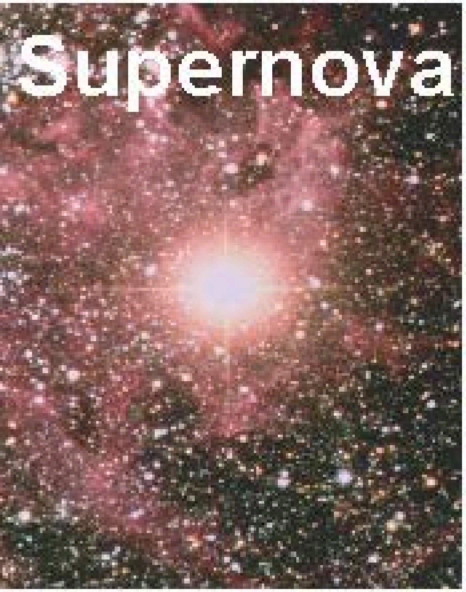
#1 of top 10 breakthroughs in physics in 2013 judged by Physics World

※energy scale

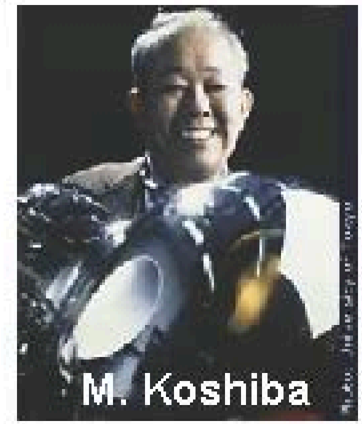
MeV=10^6 eV, GeV=10^9 eV, TeV=10^{12} eV, PeV=10^{15} eV, EeV=10^{18} eV, ZeV=10^{21} eV



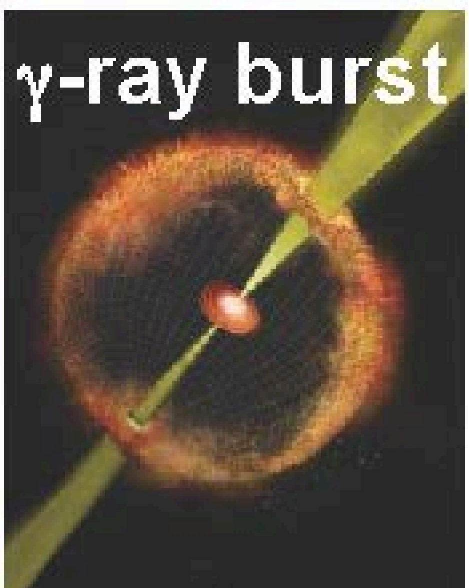
Motivation I: Unique Probe of Cosmic Explosions



~10 MeV neutrinos from supernova
thermal: gravitational energy of a star



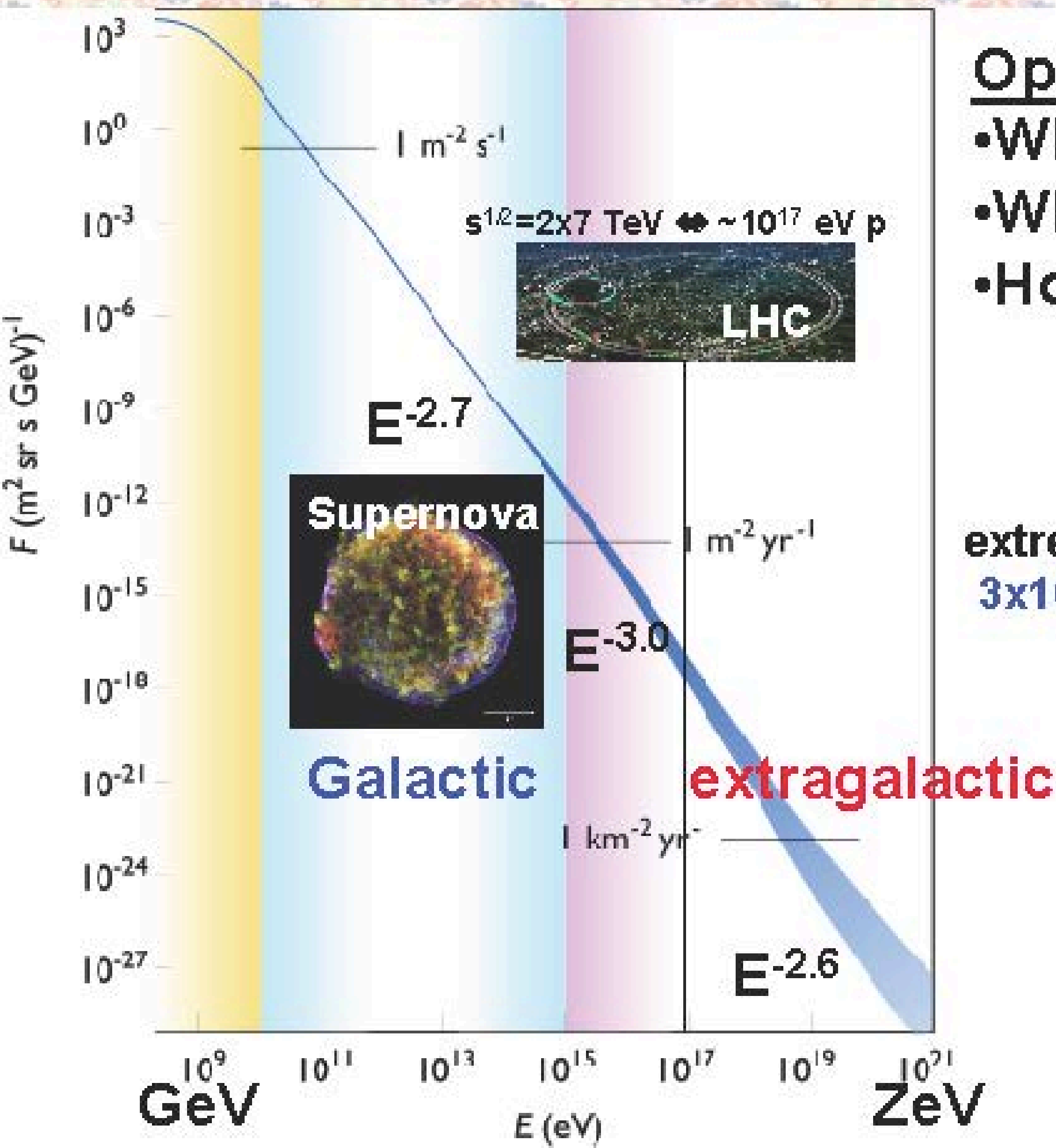
- explosion mechanism
- progenitor/ν properties



> GeV neutrinos from γ-ray bursts
nonthermal: dissipation of jets

- physics of relativistic jets (Γ~100)
- SN-GRB connection

Motivation II: Cosmic Rays - A Century Old Puzzle

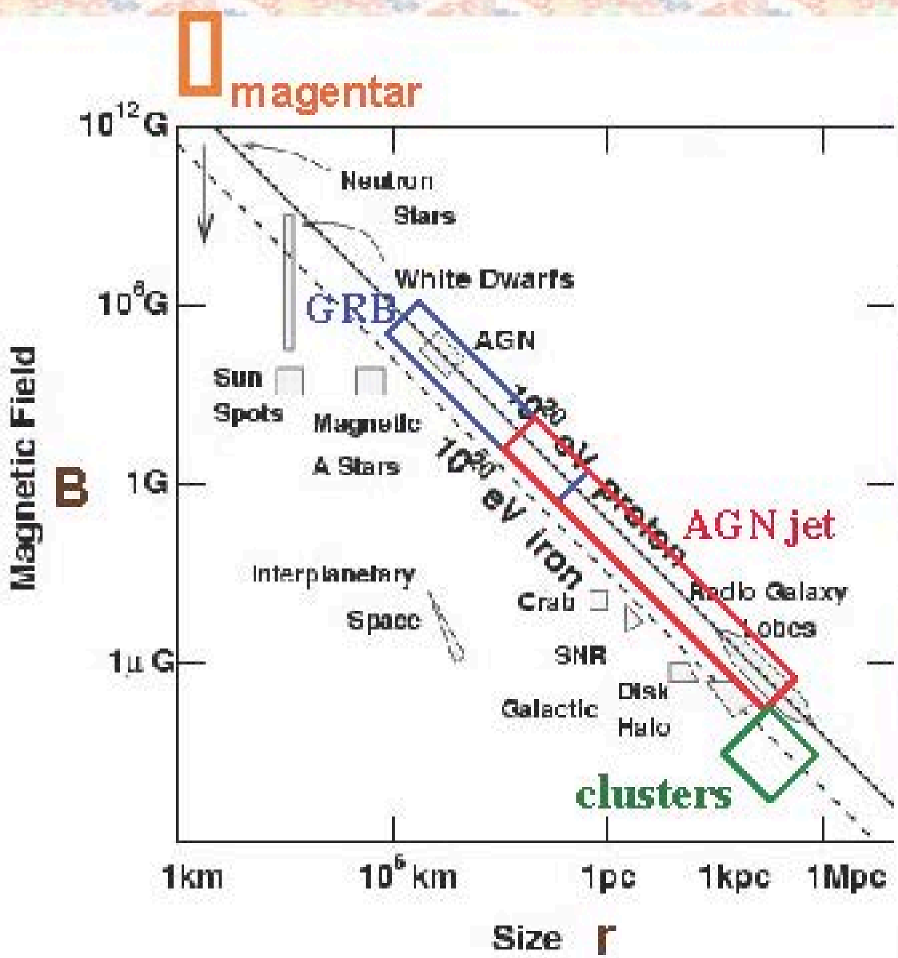


Open problems

- What is the CR origin?
- Where is the transition?
- How are CRs accelerated?

extremeness of ultrahigh-energy CRs
3×10^{20} eV ~ 160 km/h tennis ball kin.

UHECR Source Candidates: Cosmic Monsters!



Hillas condition
$E < e B r \beta$

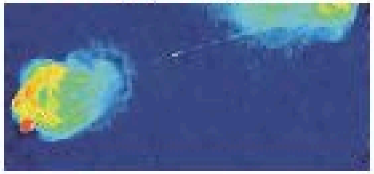
Magnetar

The strongest mag. fields
$B \sim 10^{15}$ G

γ-ray burst (GRB)

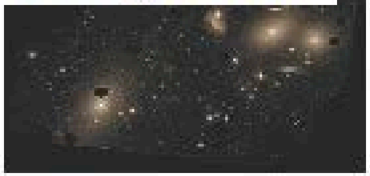
The brightest explosions
$L_\gamma \sim 10^{52}$ erg/s

Active galaxy (AGN)



The most massive black holes
$M_{BH} \sim 10^{8\text{-}9} M_{sun}$

Galaxy cluster



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

cf. $B_{sun} \sim 1$ G, $L_{sun} \sim 4\times10^{33}$ erg/s,
$M_{sun} \sim 2\times10^{33}$ g, $R_{sun} \sim 7\times10^{10}$ cm

- **Neutrinos**
  direct probe of ion acceleration
  (straight, negligible absorption)

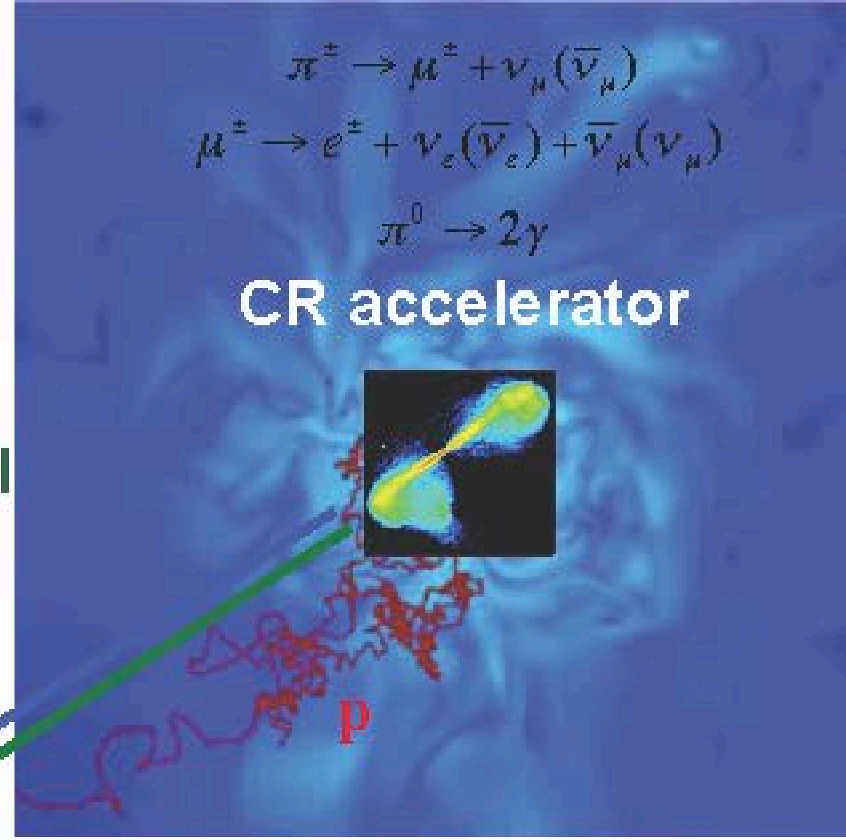
- **Gamma rays**
  contamination by leptonic signal
  interacting w. photons

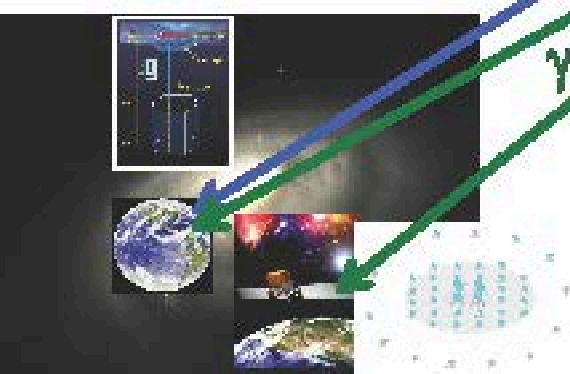
$$\gamma + \gamma \rightarrow e^{+} + e^{-}$$

$$e + \gamma \rightarrow e + \gamma \text{ (inverse-Compton)}$$

$$e + B \rightarrow e + \gamma \text{ (synchrotron)}$$

es are deflected by
magnetic fields

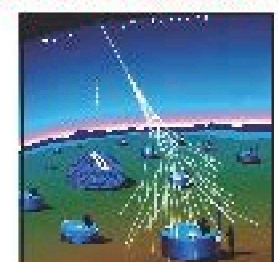




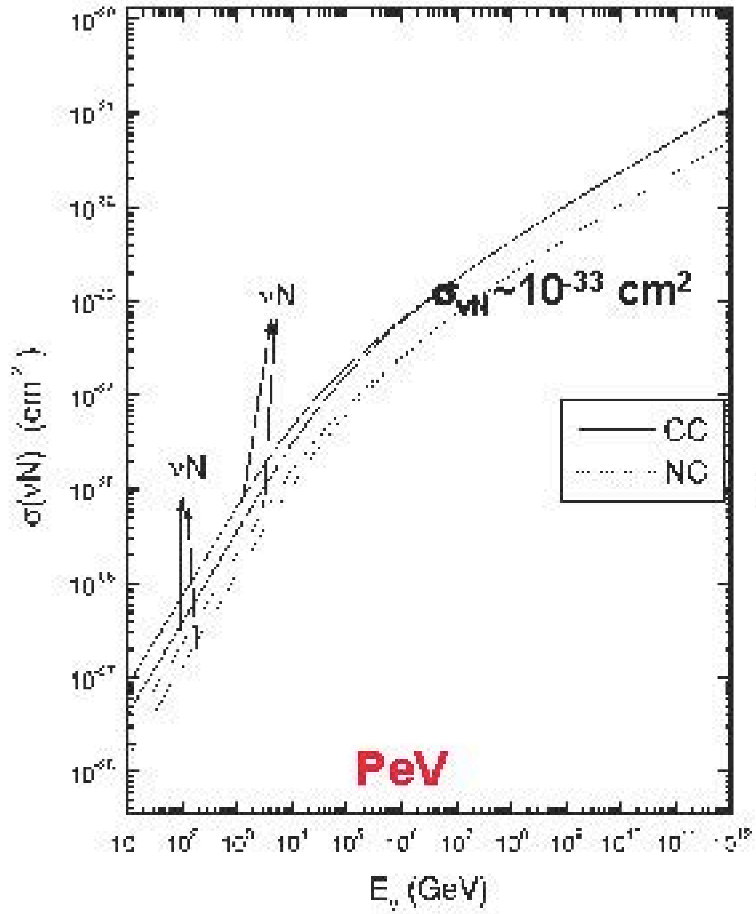
- **Cosmic rays**
  deflected by magnetic fields
  interacting w. photons/matter

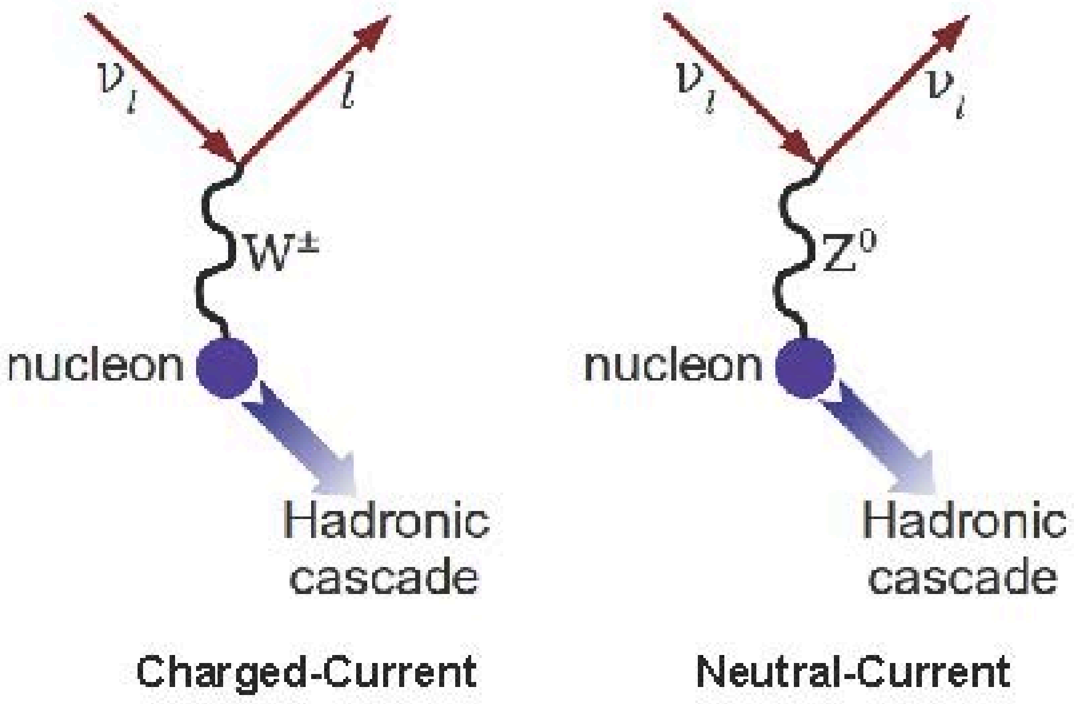
$$p + \gamma \rightarrow p / n + N\pi$$

$$p + \gamma \rightarrow p + e^{+} + e^{-}$$



Neutrino: Weak Interaction

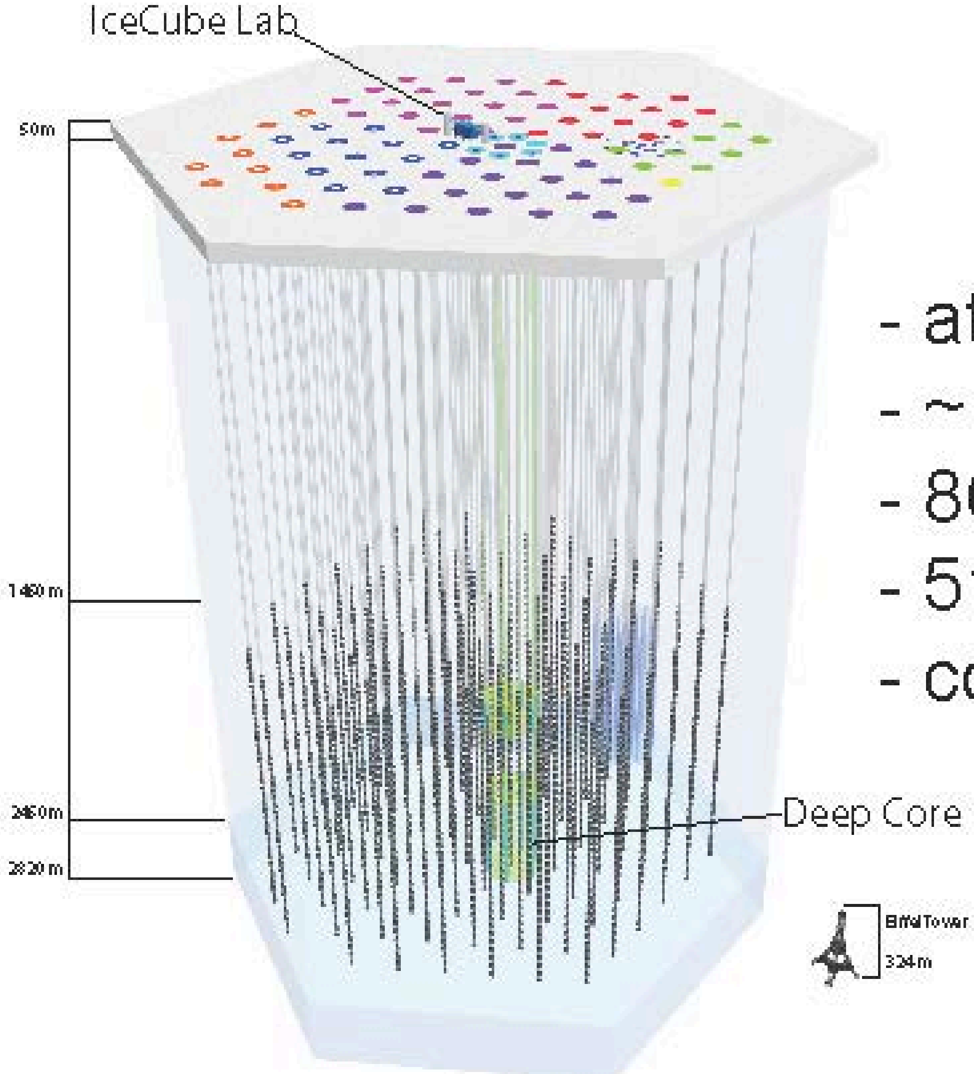




crude estimate at PeV energies

$$\mathcal{N} \sim (\varepsilon_\nu \Phi_\varepsilon)\sigma_{\nu N}(2\pi N_A \rho V) \simeq 10\ \mathrm{yr}^{-1} \left(\frac{\varepsilon_\nu^2 \Phi_\varepsilon}{10^{-8}\ \mathrm{GeV\ cm^{-2}\ s^{-1}\ sr^{-1}}}\right)\left(\frac{V}{\mathrm{km}^3}\right)$$

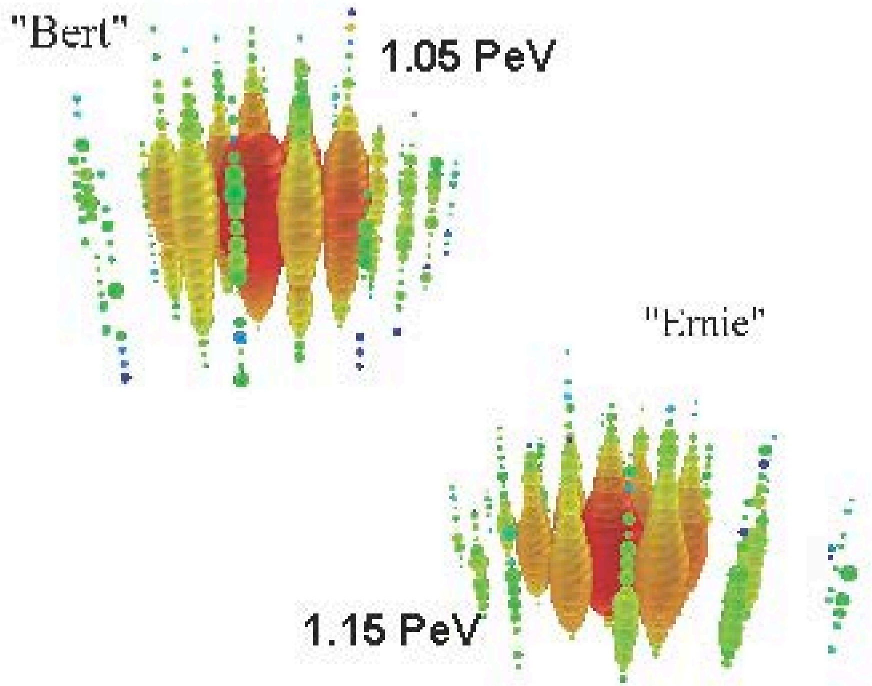
IceCube: Gton Neutrino Detector



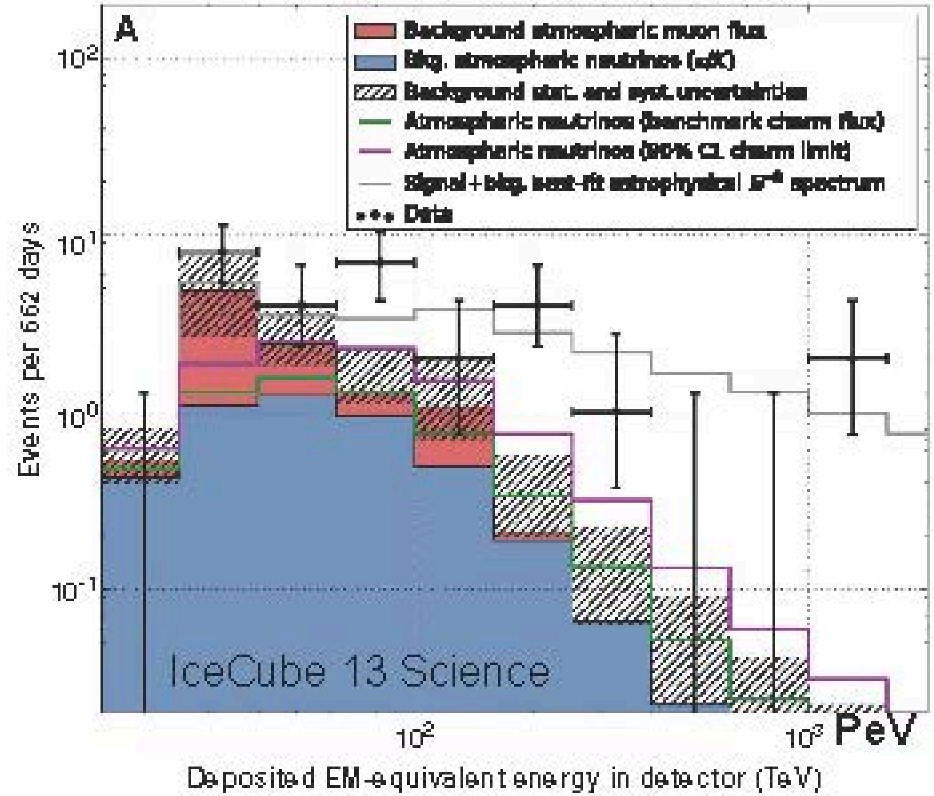
- at south pole
- ~ 1 km^3 volume ~ Gton
- 86 strings (120 m spacing)
- 5160 PMTs (17 m spacing)
- completed in 2010

IceCube Detection of High-Energy Neutrinos

First detection of PeV events (~2.8σ)



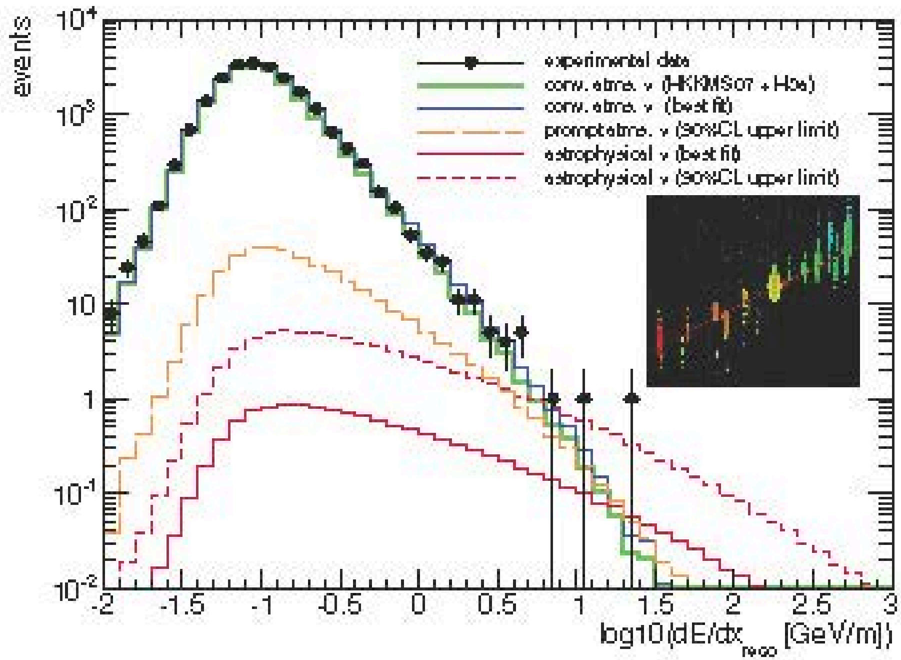
Follow-up analysis (~4.8σ)

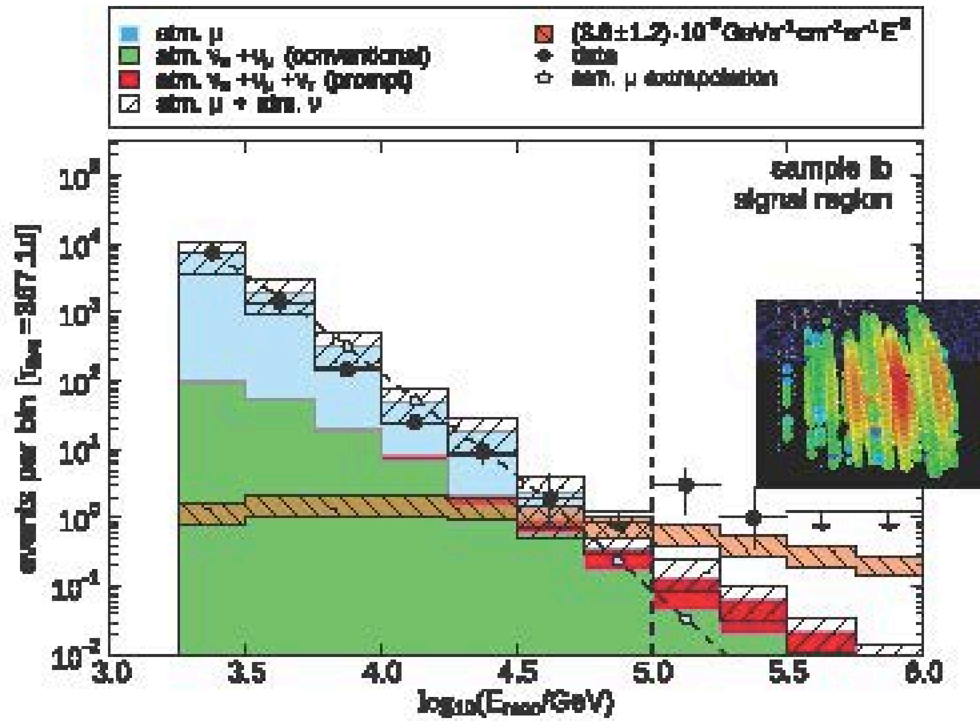


- $E_\nu^2\ \Phi_\nu$=(1.2±0.4)x10^{-8} GeV cm^{-2} s^{-1} sr^{-1} (per flavor)
- Favoring cutoff at ~2 PeV for E_ν^{-2} or steeper than $E_\nu^{-2.2}$
- Consistent w. flavor ratio 1:1:1

Hints from Classical Strategy

- IC59 upgoing track (1.8σ)
- IC40 shower (2.7σ)





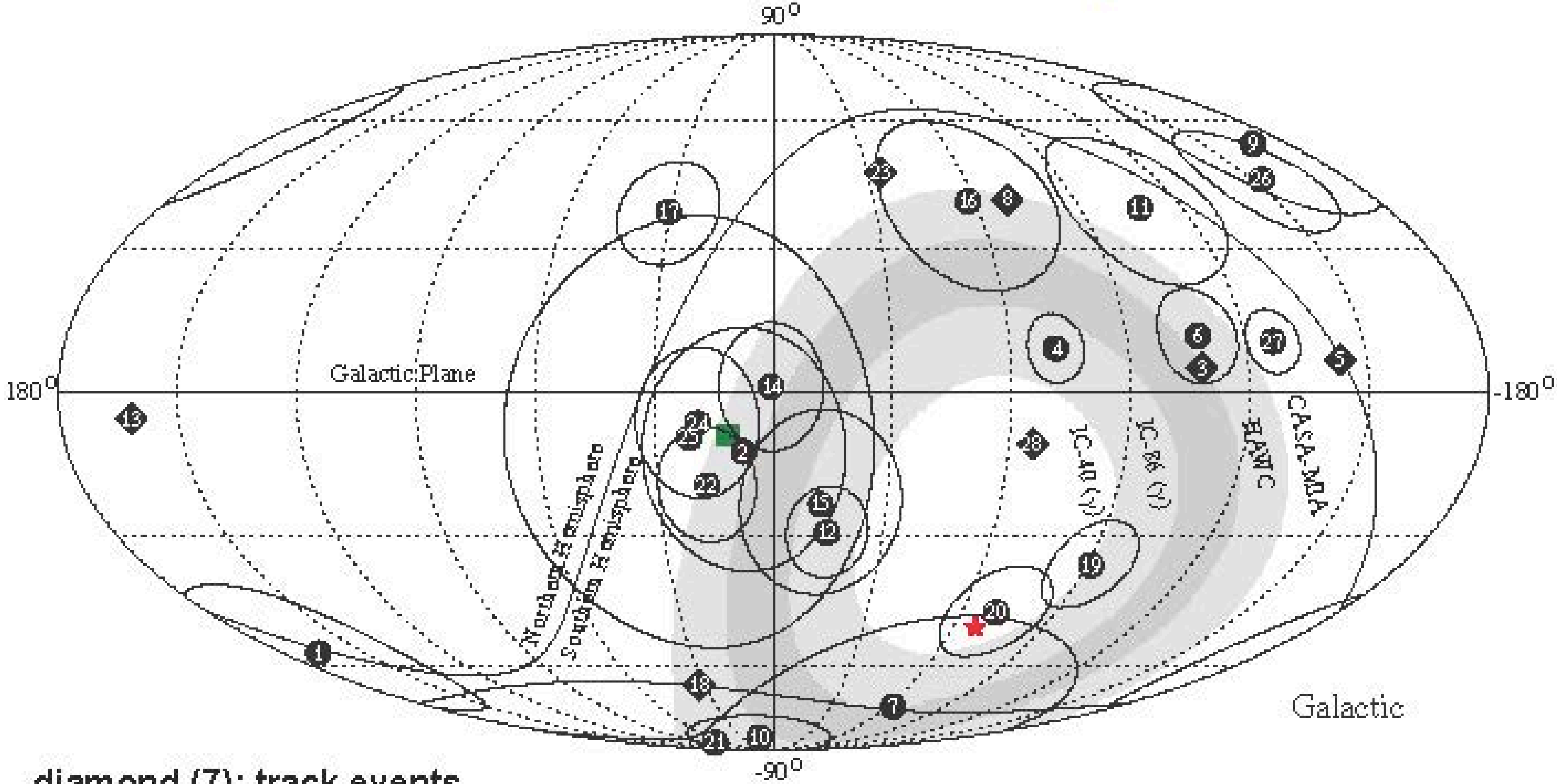
IC59 muon neutrino limit
became worse than IC40 limit

IceCube 1311.7048

IceCube 1312.0104

High-Energy Neutrino Sky Map

consistent w. isotropic distribution



diamond (7): track events
circle (21): shower event

Ahlers & KM 13; complied from IceCube 13 Science

Demystifying the Origin of Diffuse PeV Neutrinos

Q. What is the Origin?

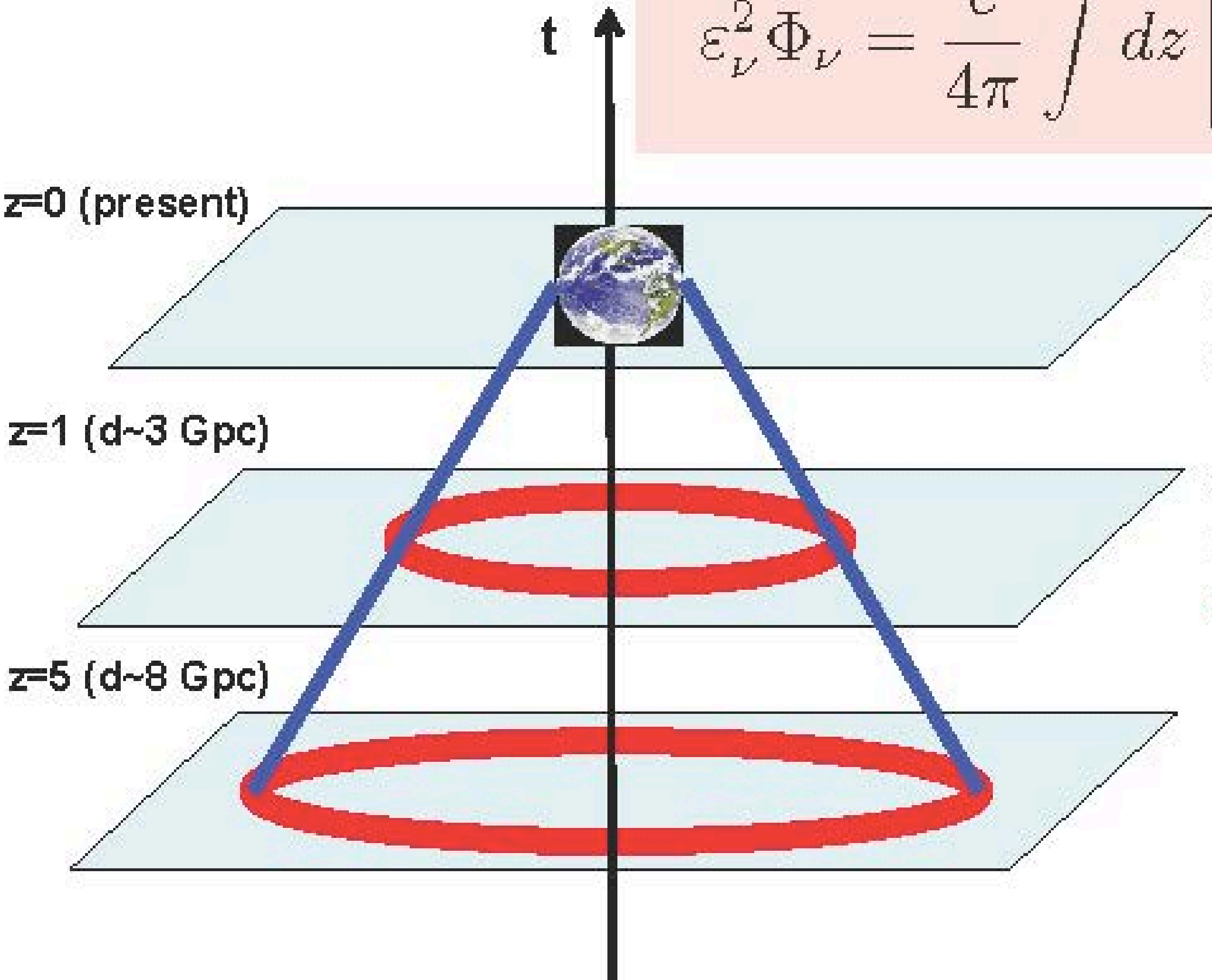
A. Not known yet. We need more statistics.
But interesting implications are obtained.

Requirements: isotropic flux w. $E_\nu^2 \Phi_\nu \sim 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1}
(break/cutoff around PeV for hard spectra)

Isotropic Diffuse Flux → Cosmic Background

It is typically difficult to detect individual HE ν sources

$$\varepsilon_\nu^2 \Phi_\nu = \frac{c}{4\pi} \int dz \left| \frac{dt}{dz} \right| \varepsilon_\nu^2 q_\nu(\varepsilon_\nu) F(z)$$



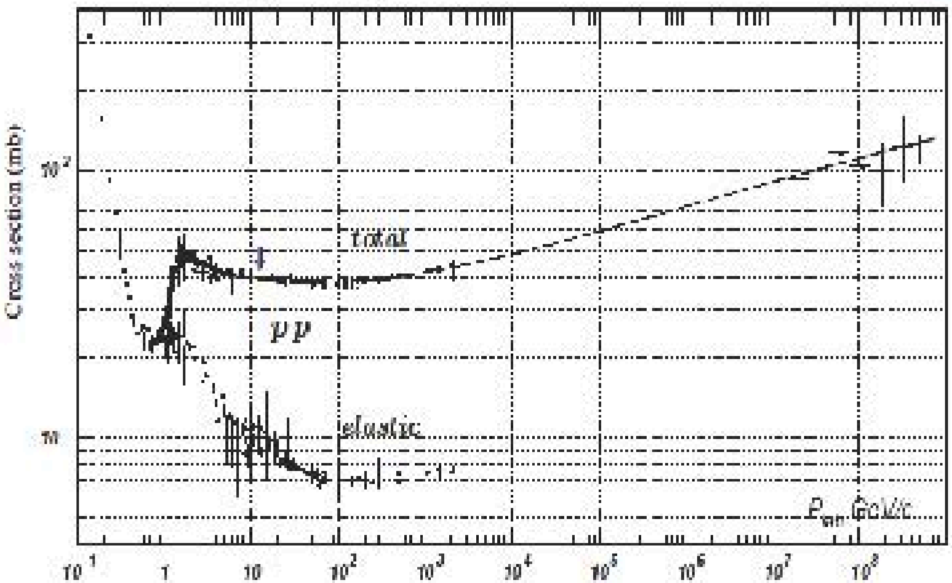
F(z): source redshift evolution function (typically max. at z~1-2)

$\varepsilon_\nu^2\, q(\varepsilon_\nu)$: ν generation rate per volume (source physics involved)

Neutrino Production Processes? pp vs pγ

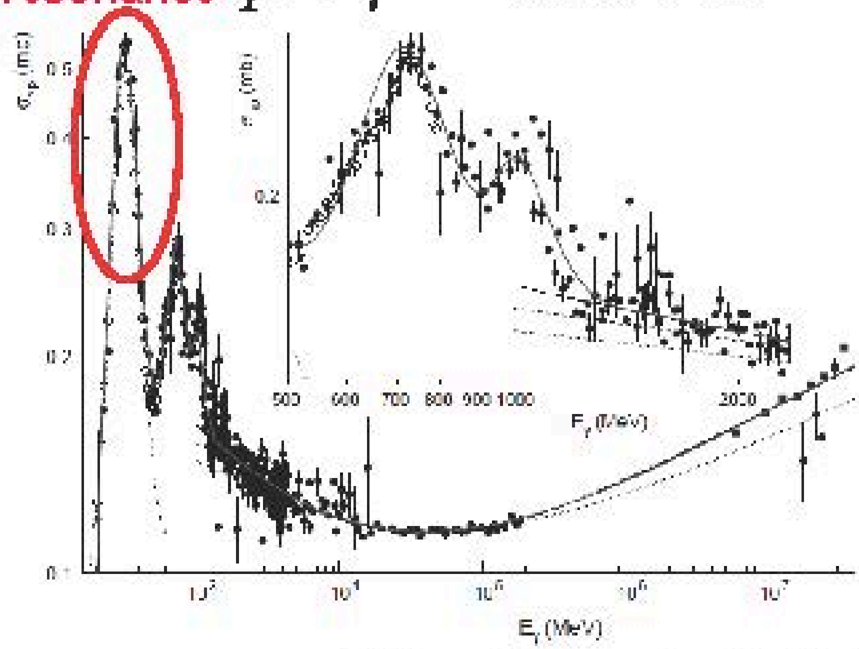
$$\pi^{\pm} \rightarrow \nu_{\mu} + \bar{\nu}_{\mu} + \nu_{e}(\bar{\nu}_{e}) + e^{\pm} \qquad \pi^{0} \rightarrow \gamma + \gamma$$

$$p + p \rightarrow N\pi + X$$



Δ-resonance

$$p + \gamma \rightarrow N\pi + X$$



σ_{pp}~$1/m_{\pi}^2$~30 mb $\pi^{\pm}:\pi^0$~2:1

$\sigma_{p\gamma}$~$\alpha\sigma_{pp}$~0.5 mb $\pi^{\pm}:\pi^0$~1:1

$\varepsilon'_p\varepsilon'_\gamma$ ~ (0.34 GeV)(m_p/2) ~ 0.16 GeV^2

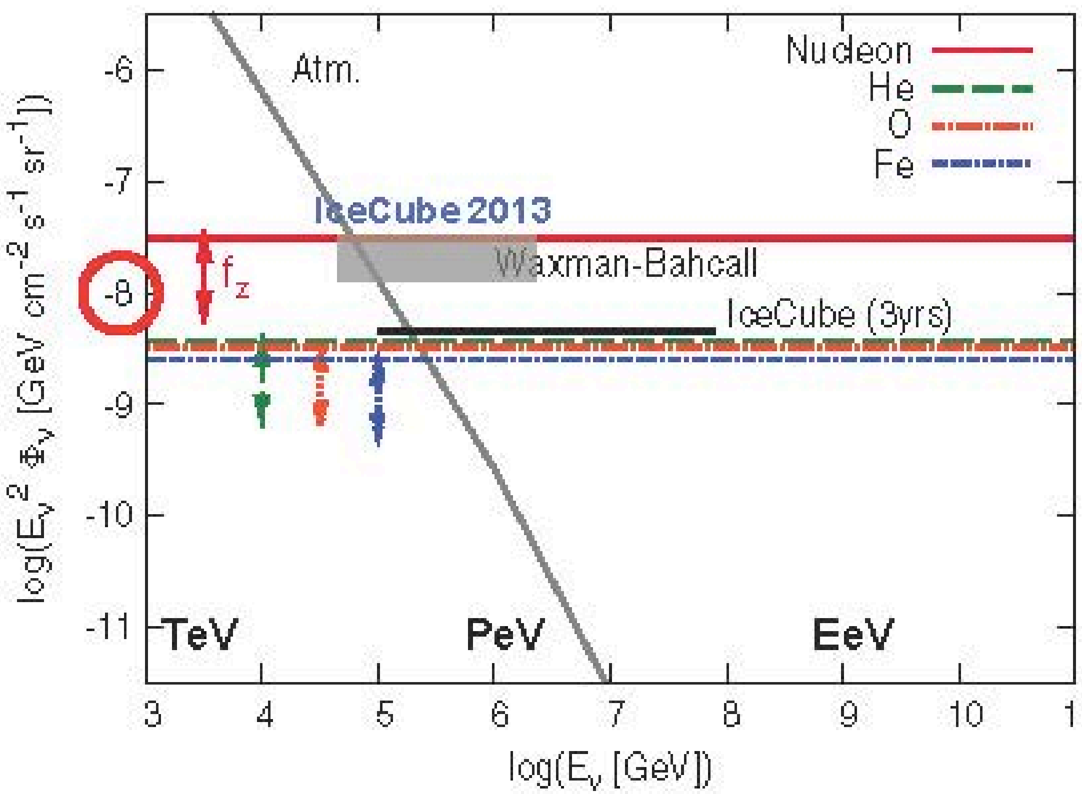
E_ν ~ 0.04 E_p: PeV neutrino ⇔ 20-30 PeV proton (or nucleon)

$$\varepsilon_\nu^2 \Phi_\nu = \frac{c}{4\pi} \int dz \left| \frac{dt}{dz} \right| \varepsilon_\nu^2 q_\nu(\varepsilon_\nu) F(z) \Longrightarrow E_\nu^2 \Phi_\nu \approx \frac{c t_H}{4\pi} \left[\frac{f_{\rm mes}}{4} \varepsilon_p^2 q_p(\varepsilon_p) \right] f_z$$

f_{mes} (<1): meson production efficiency (ex. $f_{p\gamma} \sim 0.2 n_\gamma \sigma_{p\gamma} \Delta$)
f_z (~0.6-5): source redshift evolution
$\varepsilon_p^2 q(\varepsilon_p)$: CR energy generation rate per volume

Waxman-Bahcall bound: $\varepsilon_\nu^2 \Phi(\varepsilon_\nu) < f_z \times 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1}

obs. UHECR flux: $\varepsilon_p^2 q(\varepsilon_p) = 0.6 \times 10^{44}$ erg Mpc^{-3} yr^{-1} & $f_{mes} \rightarrow 1$ limit



← **"nucleus-survival" bounds**
(KM & Beacom 10 PRD)
$\because \sigma_{A\gamma} \gg \sigma_{p\gamma}$

Q. What is the Origin?

A. Not known yet. We need more statistics.
But interesting implications are obtained.

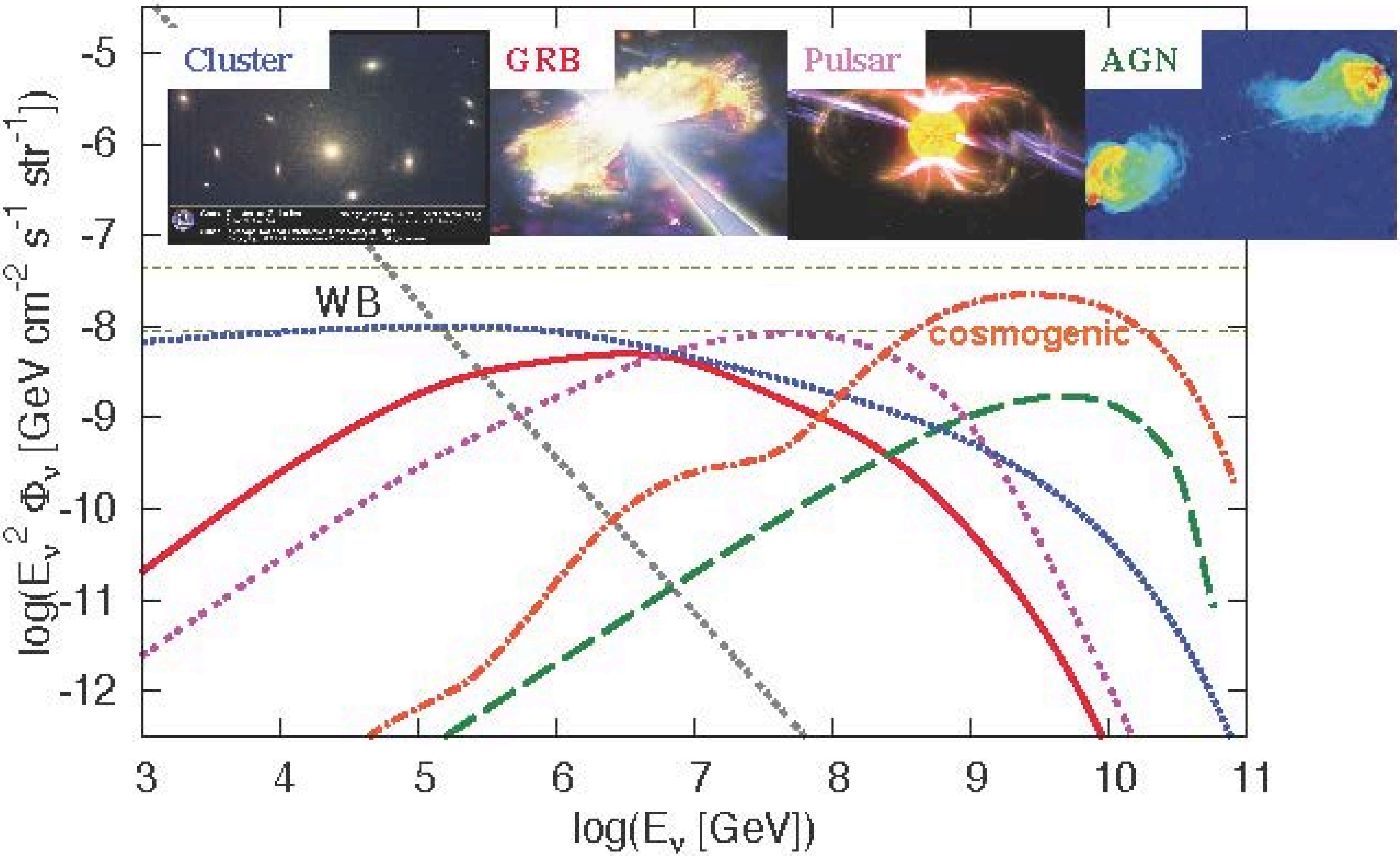
Requirements: isotropic flux w. $E_\nu^2 \Phi_\nu \sim 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1}
(break/cutoff around PeV for hard spectra)

candidate extragalactic sources (proposed before IceCube)

- γ-ray bursts (ex. Waxman & Bahcall 97, Waxman & Bahcall 00 ApJ, KM et al. 06)
- active galaxies (ex. Stecker et al. 91, Mannheim 95)
- newborn magnetars (ex. KM, Meszaros & Zhang 09)
- starburst galaxies (ex. Loeb & Waxman 06, Thompson et al. 07)
- galaxy clusters/groups (ex. KM et al. 08, Kotera, Allard, KM et al. 09)

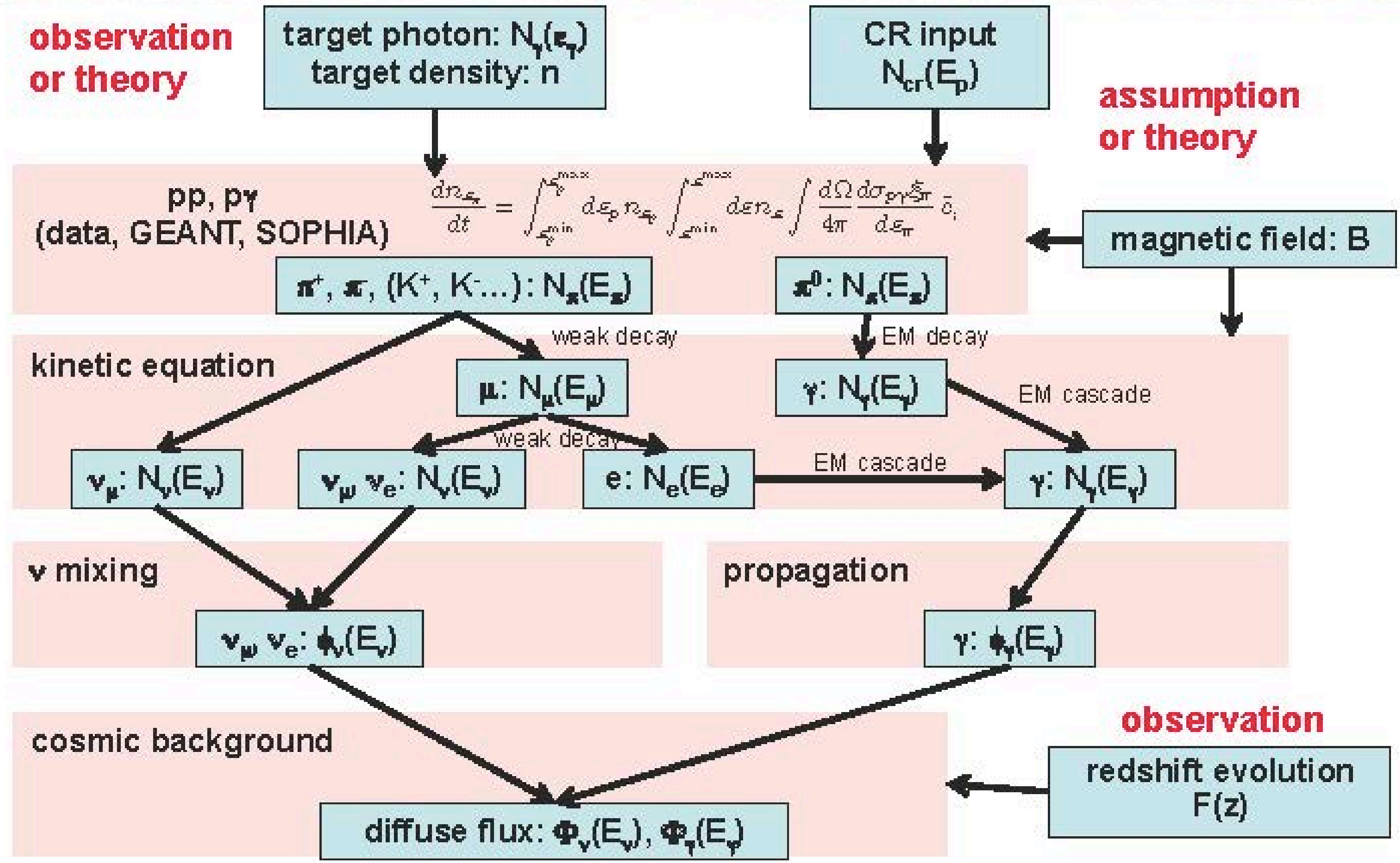
Galactic sources cannot be dominant, see Ahlers & KM 13

Now is the Time to Test Models!



taken from KM et al. 08 ApJL, KM 08 PRDR, KM et al. 09 PRD, KM 08 AIPC, Takami, KM+ 09 APh

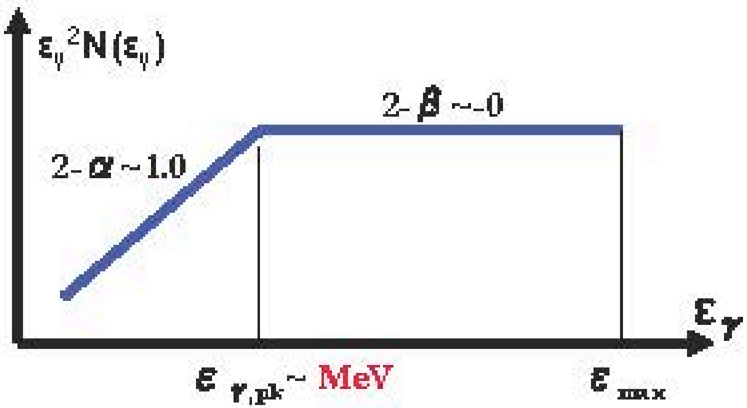
State-of-the-Art Theoretical Calculations



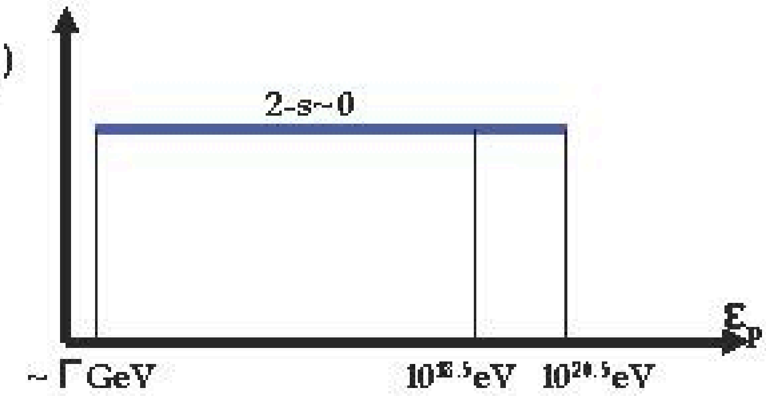
e.g., KM 07 PRD

Example: Gamma-Ray Bursts

Photon Spectrum (observed)

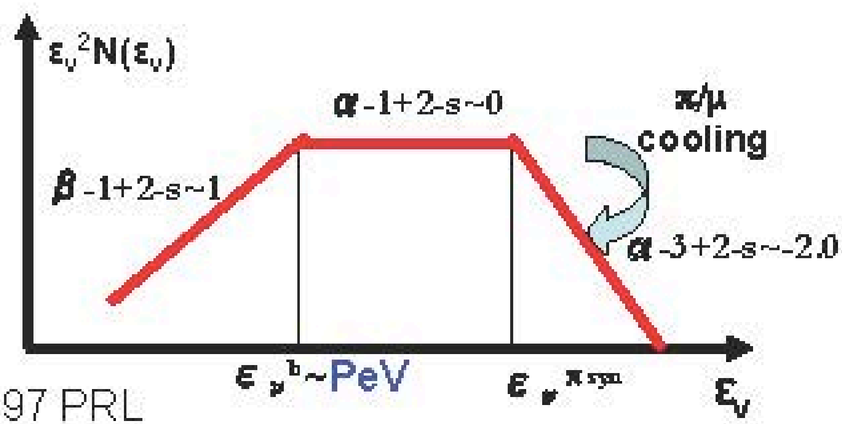


CR Spectrum (Fermi mechanism)



$\varepsilon_p \varepsilon_\gamma \sim 0.2\Gamma^2$ GeV^2
at Δ-resonance

Neutrino Spectrum



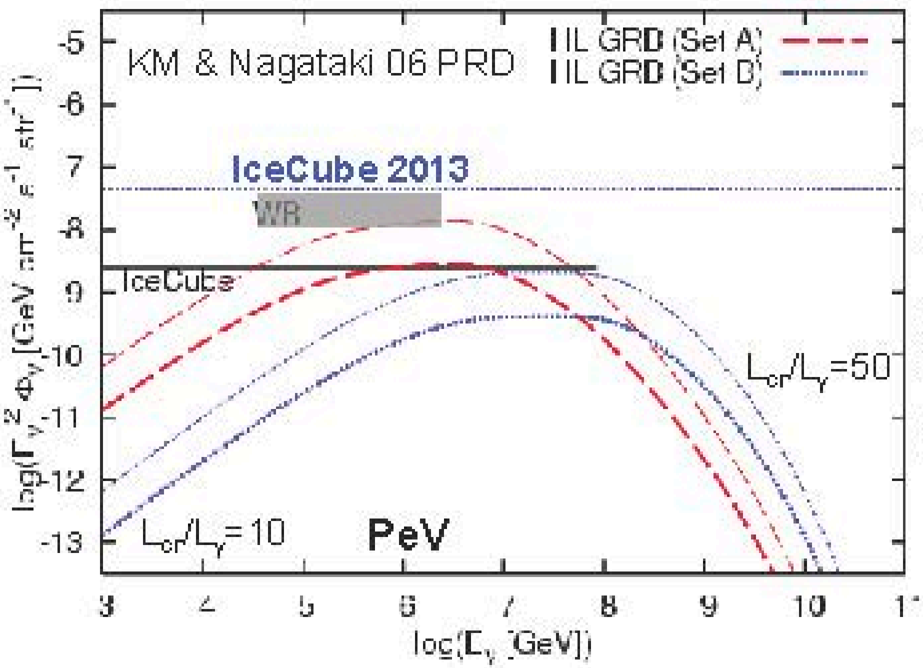
$\varepsilon_\nu{}^2 N(\varepsilon_\nu) \sim (1/4) f_{p\gamma} \varepsilon_p{}^2 N(\varepsilon_p)$
efficiency: $f_{p\gamma} \sim 0.2 n_\gamma \sigma_{p\gamma} \Delta$

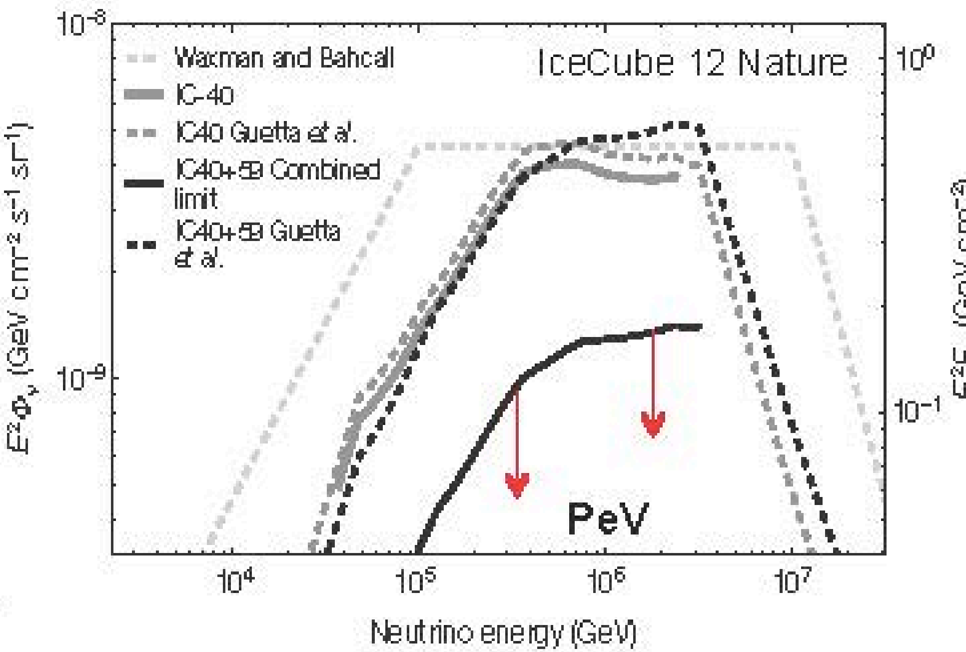
$\varepsilon_\nu{}^b \sim 0.05 \varepsilon_p{}^b$
~ 0.01 GeV^2 $\Gamma^2/\varepsilon_{\gamma,pk}$
~1 PeV (w. $\varepsilon_{\gamma,pk}$~1 MeV)
Γ~300: jet Lorentz factor

Waxman & Bahcall 97 PRL

Gamma-Ray Bursts (pγ)

numerical results w. detailed microphysics





GRBs are special since stacking analyses are possible

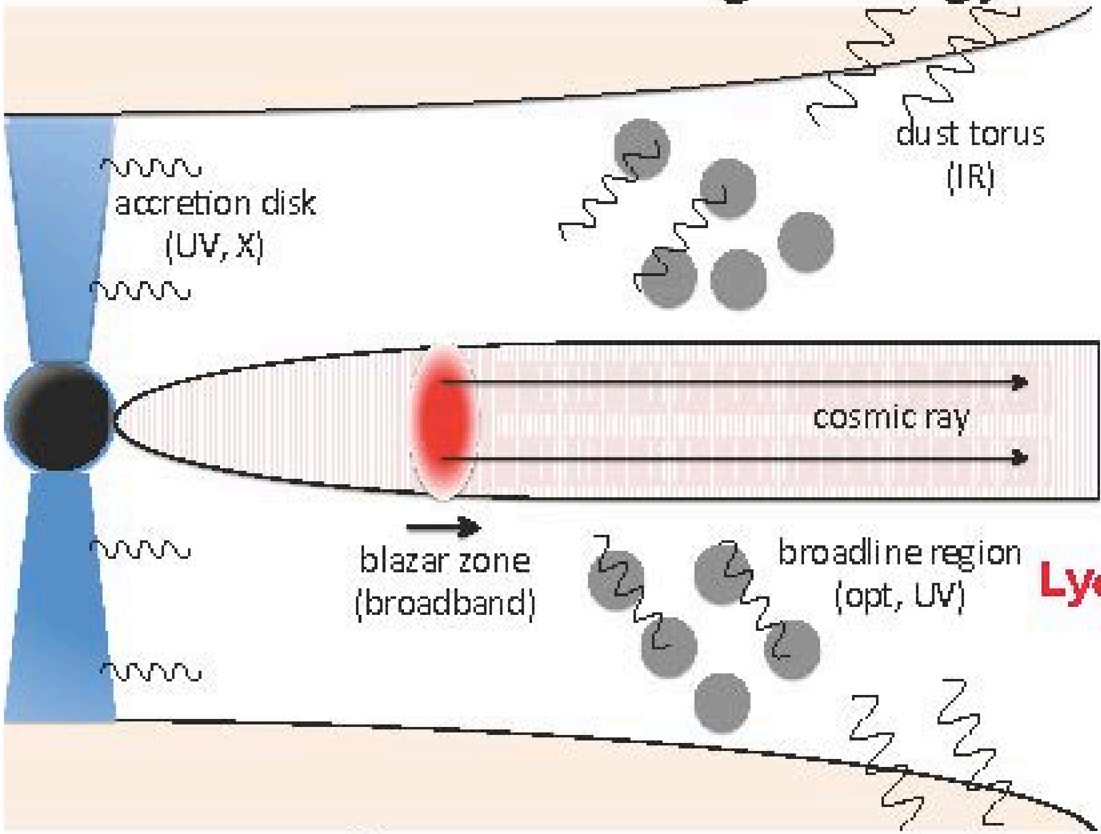
duration~10-100 s → atm. bkg. is negligible for typical GRBs

Stacking analyses imply <~ 10^{-9} GeV cm^{-2} s^{-1} sr^{-1} → disfavored

But different types (low-power GRBs) are viable (KM & Ioka 13 PRL)

Active Galactic Nuclei

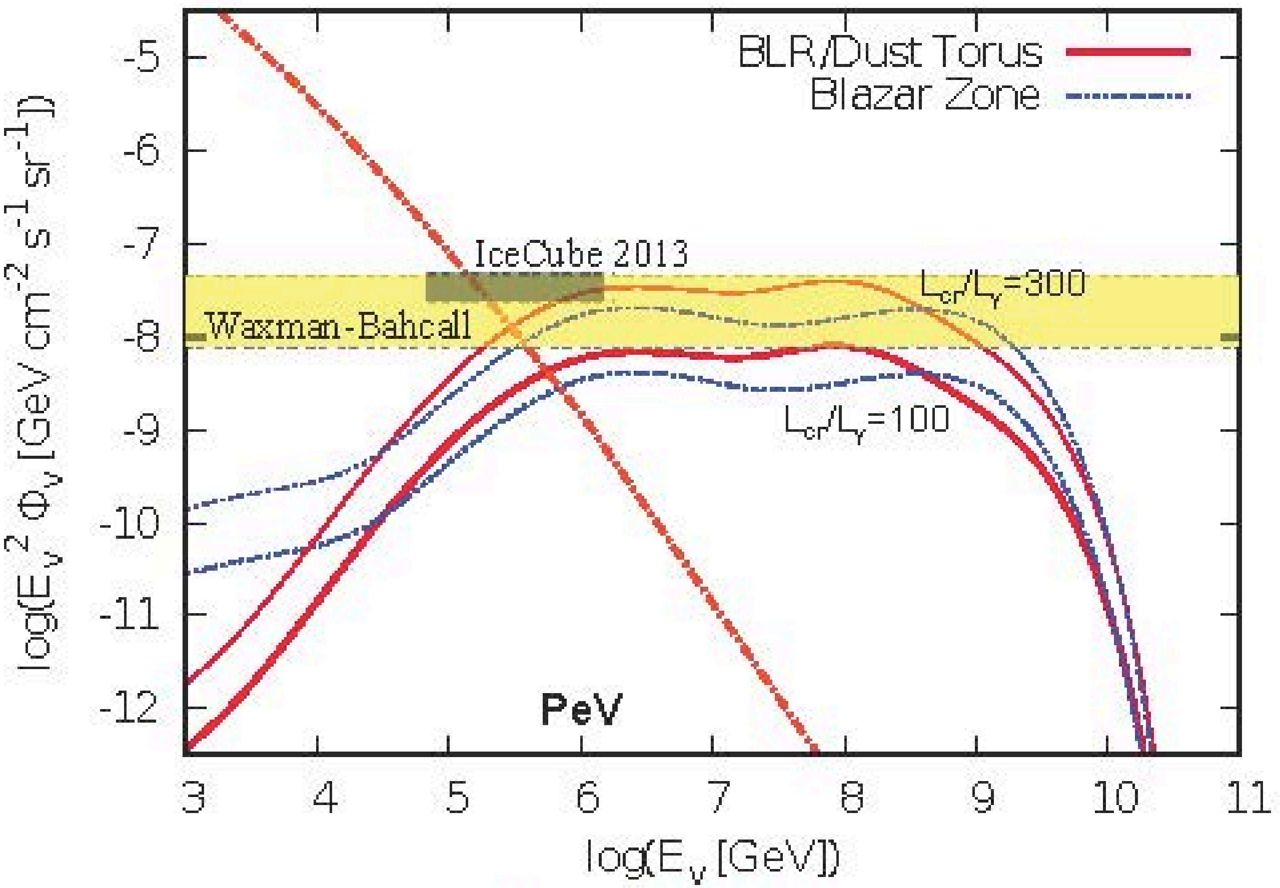
- Active galaxies are known powerful γ-ray sources
- Golden candidate sources of ultrahigh-energy cosmic rays



typical energy $E'^{b}_{\nu} \approx 0.05(0.5 m_p c^2 \bar{\varepsilon}_\Delta / E'_{\rm BL}) \simeq 0.78 \ {\rm PeV}$

efficiency $f_{p\gamma} \approx \hat{n}_{\rm BL} \sigma^{\rm eff}_{p\gamma} r_{\rm BLR} \simeq 5.4 \times 10^{-2} \ L^{1/2}_{\rm AD,46.5}$

AGN Inner Jet (pγ)



KM, Inoue & Dermer 14

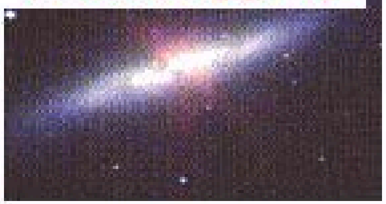
Sub-PeV ν flux is insufficient and ν spectra are too hard

→ The inner jet model does not work as it is

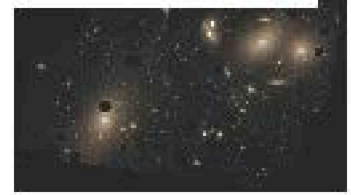
Strong prediction: cross-correlation with known <80 FSRQs

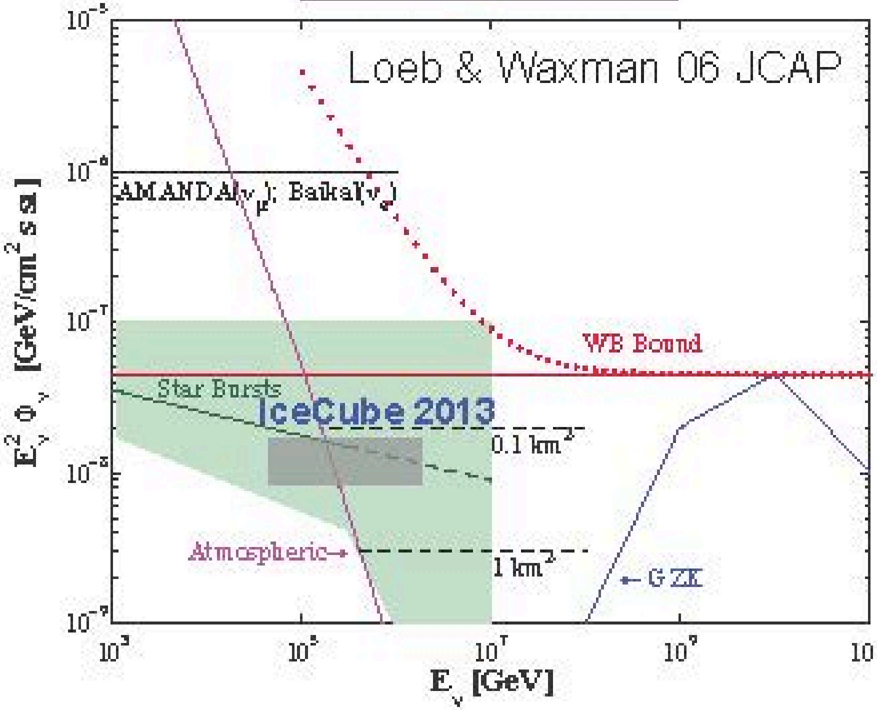
pp Scenarios: Cosmic-Ray Reservoirs

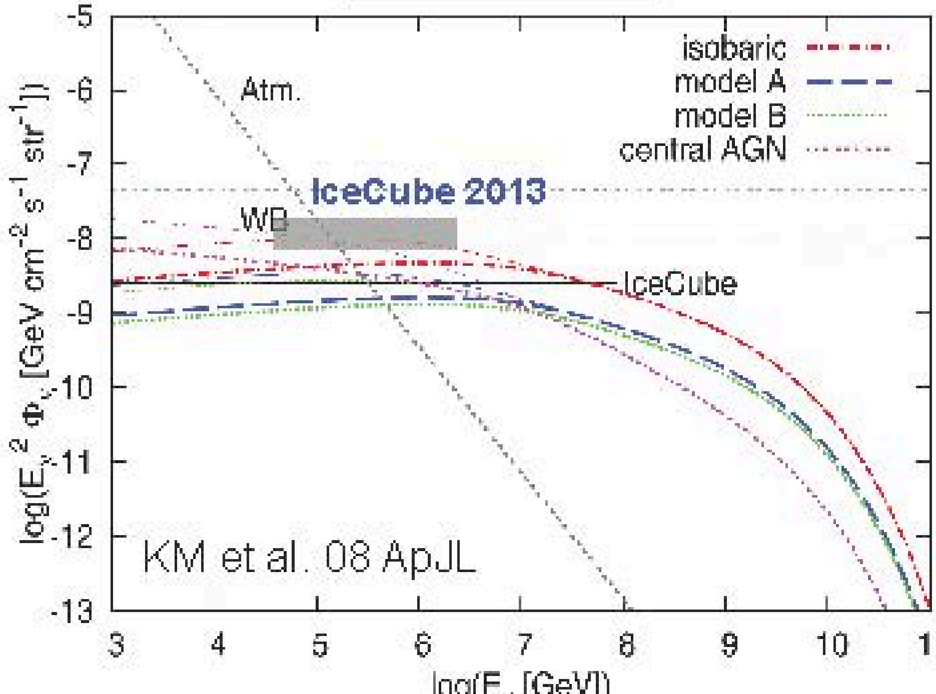
Star-forming galaxy



Galaxy cluster







- Predicted models can explain the IceCube signal
- Diffusion break or cutoff around PeV is predicted
- But each source is typically too faint to detect

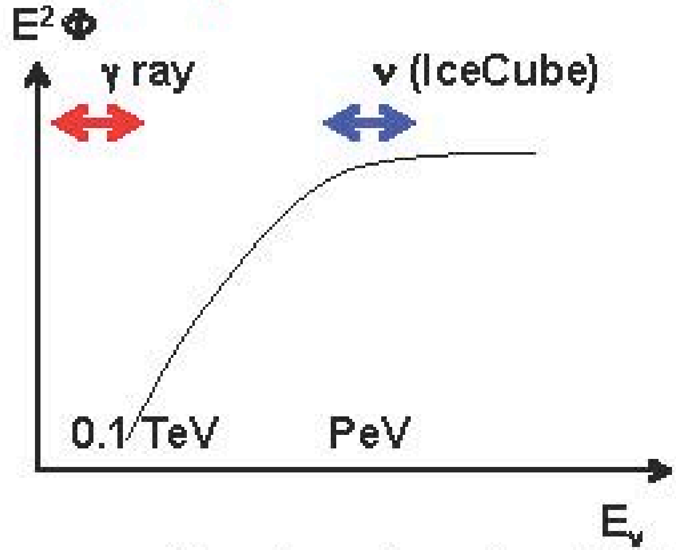
$p\gamma$ vs pp: Multi-Messenger Connection

$$p + \gamma \rightarrow N\pi + X$$

$$E_\nu^2\,\Phi_\nu \sim (1/8)\, f_{p\gamma}\, E_{CR}^2\,\Phi_{CR}$$

$$E_\gamma^2\,\Phi_\gamma \sim (1/2)\, f_{p\gamma}\, E_{CR}^2\,\Phi_{CR}$$

$$\rightarrow E_\gamma^2\,\Phi_\gamma = 4\, E_\nu^2\,\Phi_\nu\, (p\gamma)$$



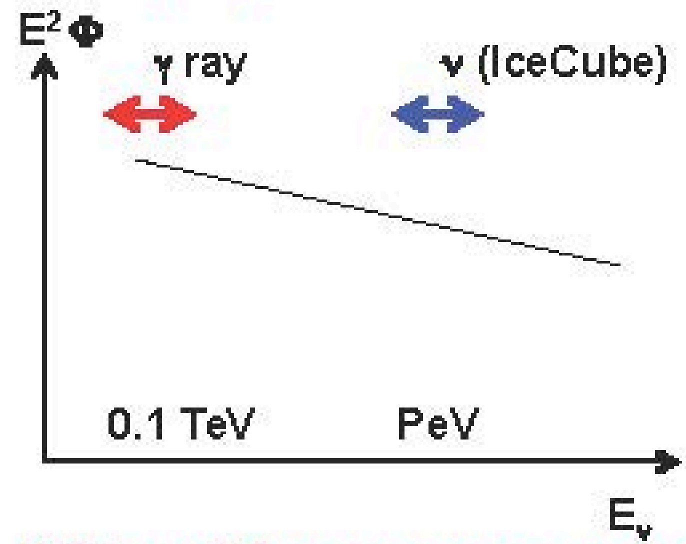
connection is quite often lost

$$p + p \rightarrow N\pi + X$$

$$E_\nu^2\,\Phi_\nu \sim (1/6)\, f_{pp}\, E_{CR}^2\,\Phi_{CR}$$

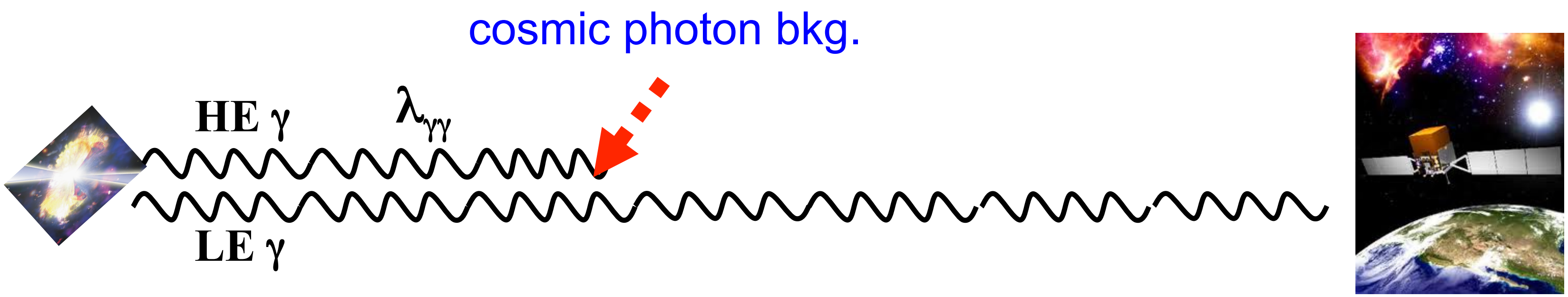
$$E_\gamma^2\,\Phi_\gamma \sim (1/3)\, f_{pp}\, E_{CR}^2\,\Phi_{CR}$$

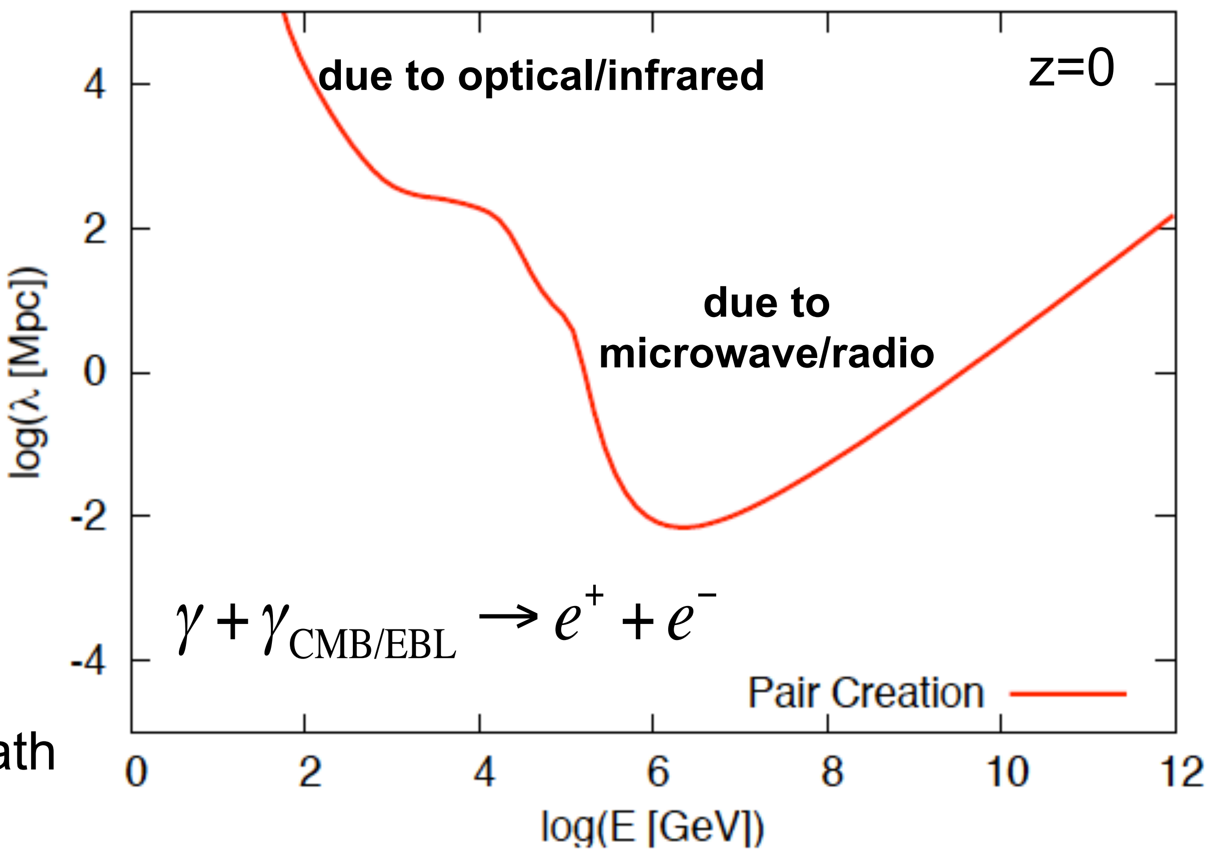
$$\rightarrow E_\gamma^2\,\Phi_\gamma = 2\, E_\nu^2\,\Phi_\nu\, (pp)$$



tight neutrino-gamma connection

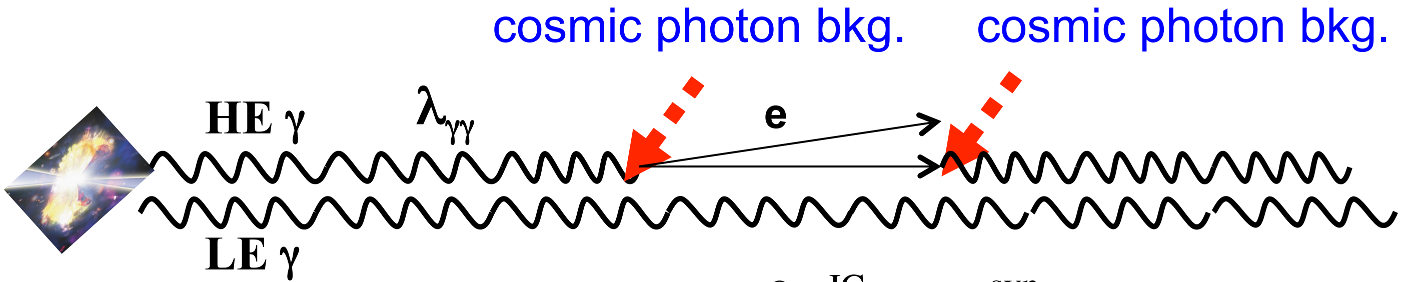
Fate of Extragalactic Gamma Rays





mean free path

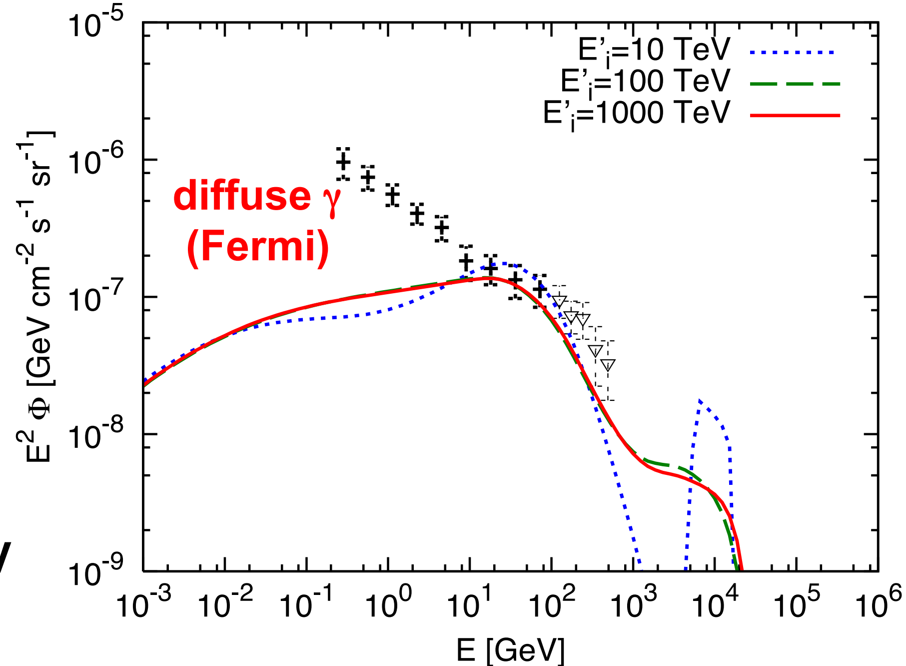
Effects of Electromagnetic Cascades



Boltzmann equation

$$\frac{\partial N_\gamma}{\partial x} = -N_\gamma R_{\gamma\gamma} + \frac{\partial N_\gamma^{\rm IC}}{\partial x} + \frac{\partial N_\gamma^{\rm syn}}{\partial x} - \frac{\partial}{\partial E}[P_{\rm ad} N_\gamma] + Q_\gamma^{\rm inj},$$

$$\frac{\partial N_e}{\partial x} = \frac{\partial N_e^{\gamma\gamma}}{\partial x} - N_e R_{\rm IC} + \frac{\partial N_e^{\rm IC}}{\partial x} - \frac{\partial}{\partial E}[(P_{\rm syn} + P_{\rm ad}) N_e] + Q_e^{\rm inj},$$



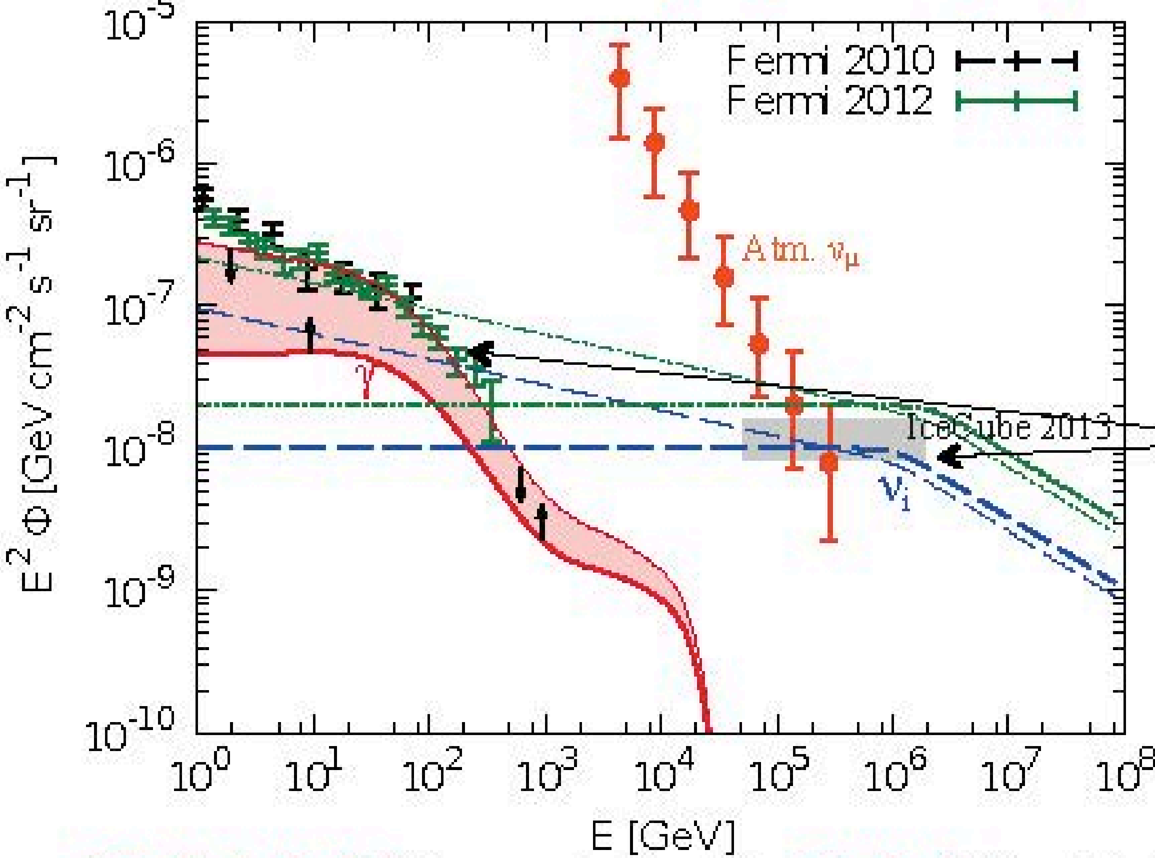
γ-ray spectra

"near-universal" at < TeV

KM, Beacom & Takami
12 JCAP

First Multi-Messenger Tests with "Measured" Fluxes

pp scenario: $E_\gamma^2 \Phi_\gamma = 2 E_\nu^2 \Phi_\nu$



KM, Ahlers & Lacki 13 PRDR

"comparable fluxes" (for all flavors)

simple but important

- Γ<2.1-2.2 (for extragal.), Γ<2.0 (gal.) (cf. Milky Way: Γ~2.7)
- contribution to diffuse sub-TeV gamma-ray flux: >30-40%
- limits are insensitive to source redshift evolution

Implications

pp scenarios can be tested in near future

- Determining Γ at sub-PeV energies by IceCube
  If $\Gamma > 2.2 \rightarrow$ pp scenarios are disfavored
- Understanding diffuse γ-ray flux at sub-TeV energies
  40%-100% from AGN $\rightarrow \Gamma$~2.0-2.1 or excluded
- Discovering individual TeV sources (by CTA, HAWC)
  The sources should show hard spectra

Need careful studies on pγ scenarios

- Uneasy for standard jet models to explain the signal
  $\rightarrow$ low-power GRBs? AGN core?
- γ-ray constraints are model dependent

Questions & Future Directions

- Spectral features; Is the neutrino break/cutoff real?
  diffusion break, π cooling, ν attenuation, maximum p energy
- Flavor ratios
  1:1:1, 0.57:1:1 (μ damp), 2.5:1:1 (n decay), others (exotic)

- Multi-messenger studies w. IceCube, Auger, HAWC, Fermi etc.;
  Connection w. origins of observed cosmic rays?
  - $E_\nu \sim 0.04\ E_p$: PeV $\nu \Leftrightarrow$ ~20-30 PeV p or ~(20-30)A PeV nuclei
  - contained CR spectrum ≠ escaped CR spectrum

  $E_\nu^2\ \Phi_\nu \sim 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1} ⇔ Waxman-Bahcall bound flux

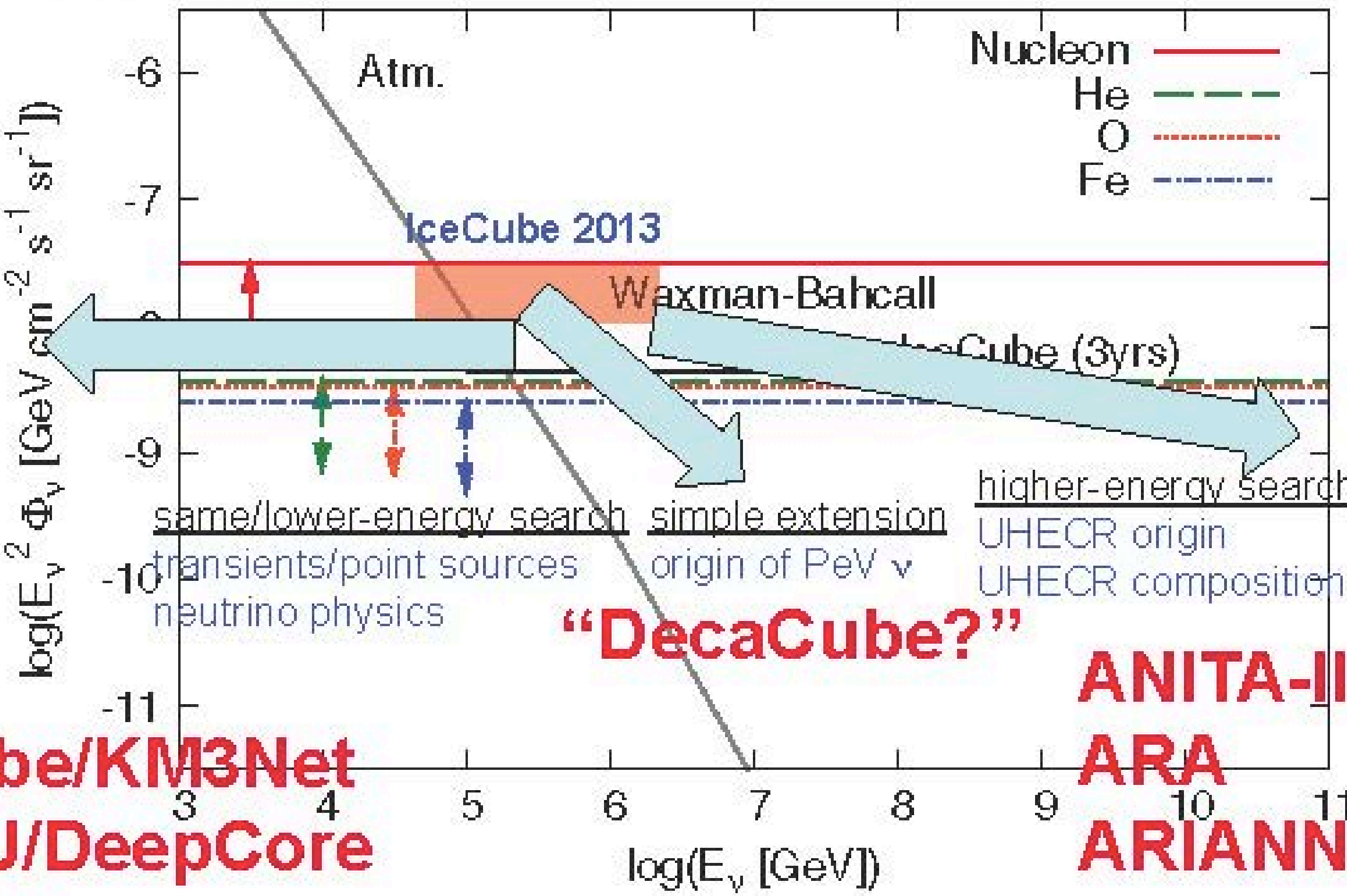
  ⬇

  a. $f_{mes} \sim 1$ & $\varepsilon_p^2 N(\varepsilon_p)|_{10\text{-}100\ PeV} \sim 10^{44}$ erg Mpc^{-3} yr^{-1} ~(obs. value)

  b. $f_{mes} << 1$ & $\varepsilon_p^2 N(\varepsilon_p)|_{10\text{-}100\ PeV} >> 10^{44}$ erg Mpc^{-3} yr^{-1}

  (The latter is more favored if UHECRs are heavy nuclei)

Hope Multiwavelength Neutrino Astrophysics



"DecaCube?"

IceCube/KM3Net
PINGU/DeepCore
Hyper-K

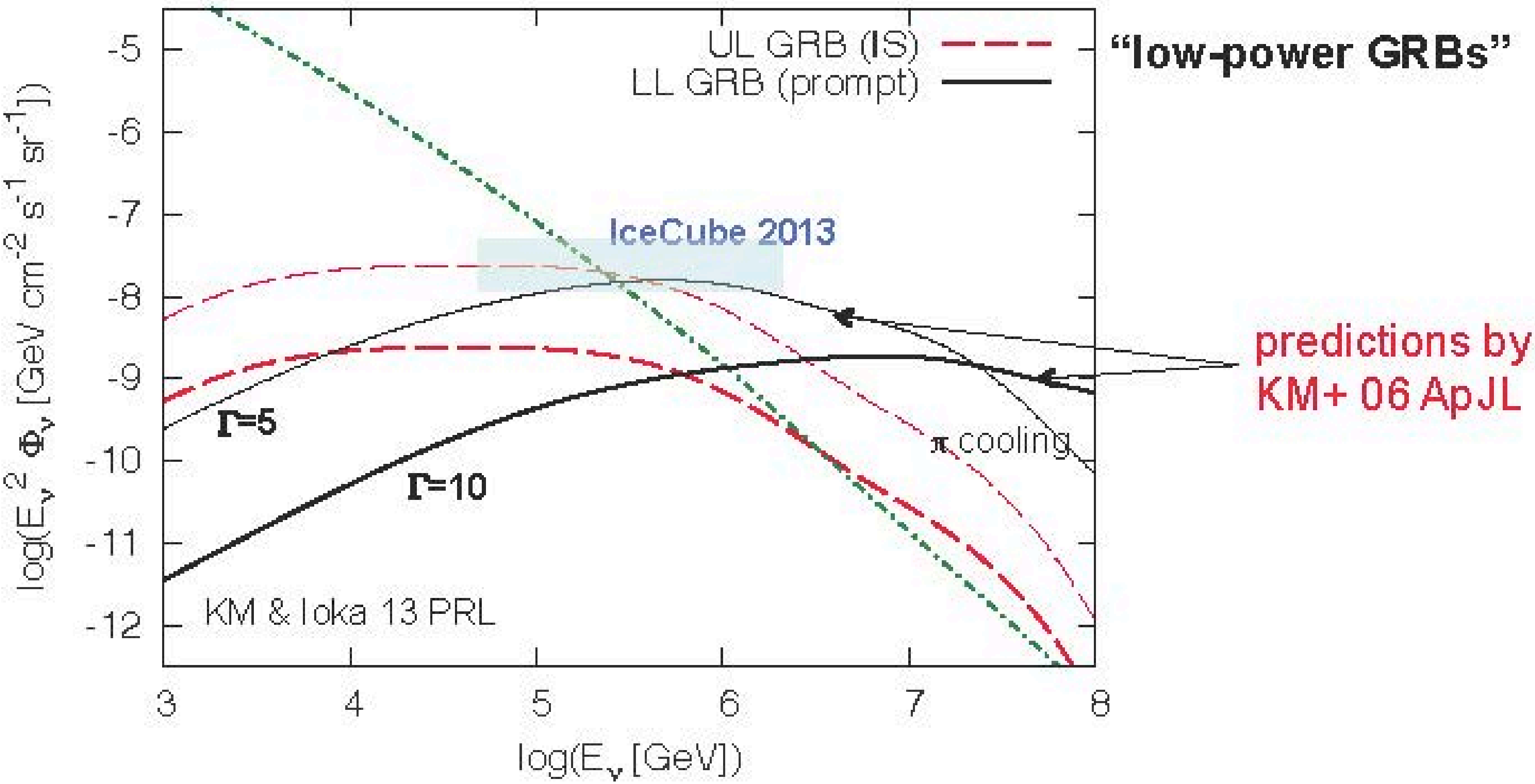
ANITA-III (2014)
ARA
ARIANNA

GeV-TeV νs are interesting for both ν physics & astrophysics!

GeV-PeV Neutrinos as a Probe of Relativistic Jets

Why Transients?

Original motivation: identifying a source of neutrinos



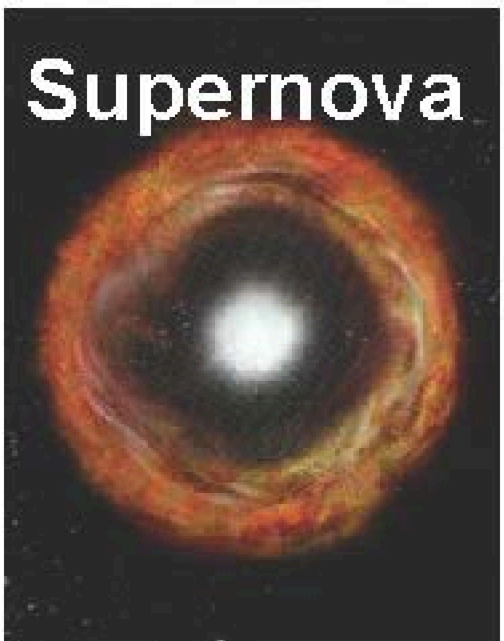
Transients → temporarily luminous and bkg. reduced

Why Transients?

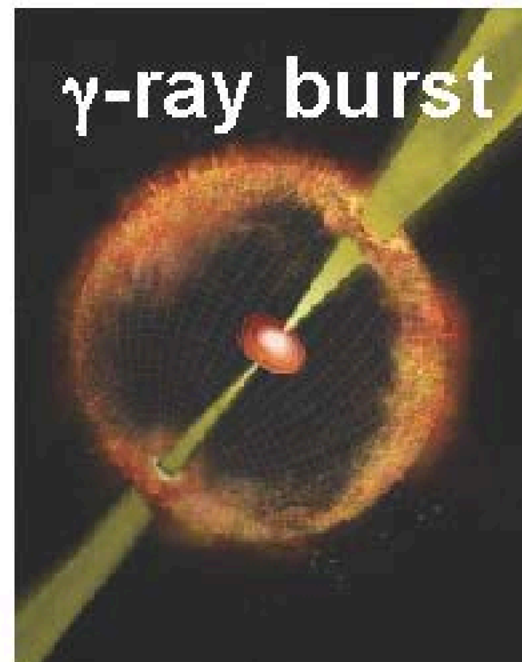
Neutrinos probe physics that cannot be studied by photons

For $\Phi_\nu \propto \varepsilon_\nu^{-2}$, $N \propto \varepsilon_\nu \Phi_\nu \rightarrow$ more statistics at lower energies

exciting targets: gamma-ray bursts & supernovae



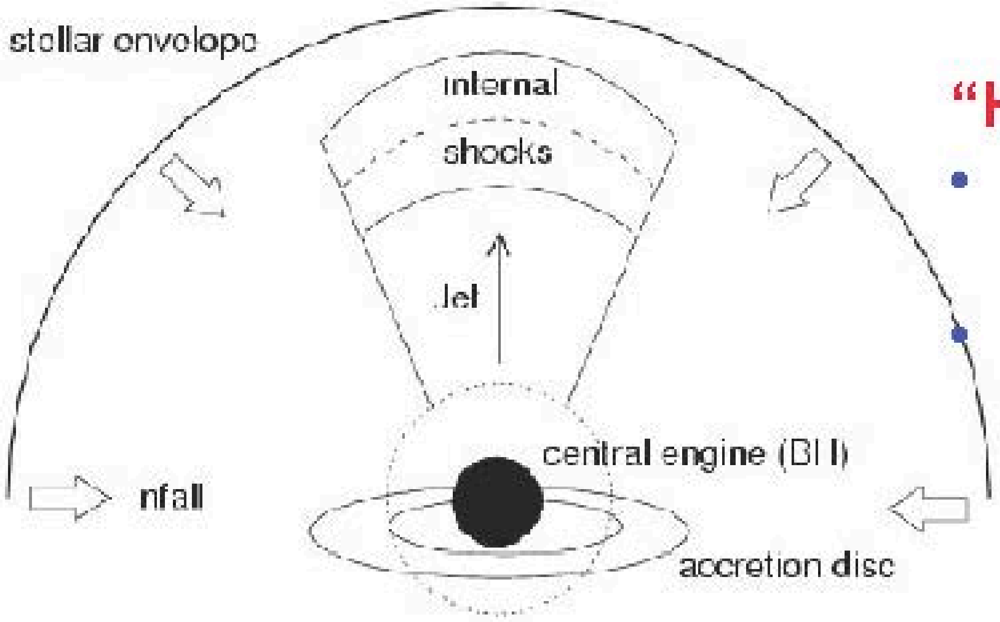
?



TeV-PeV Neutrinos as a Probe of Jets inside Stars

Motivations

- Jet acceleration and jet composition (baryonic or magnetic)
- clues to GRB-SN connection and progenitors
- Neutrino mixing including matter effects etc.



Meszaros & Waxman 01 PRL
Razzaque, Meszaros & Waxman 04 PRL
Ando & Beacom 05 PRL

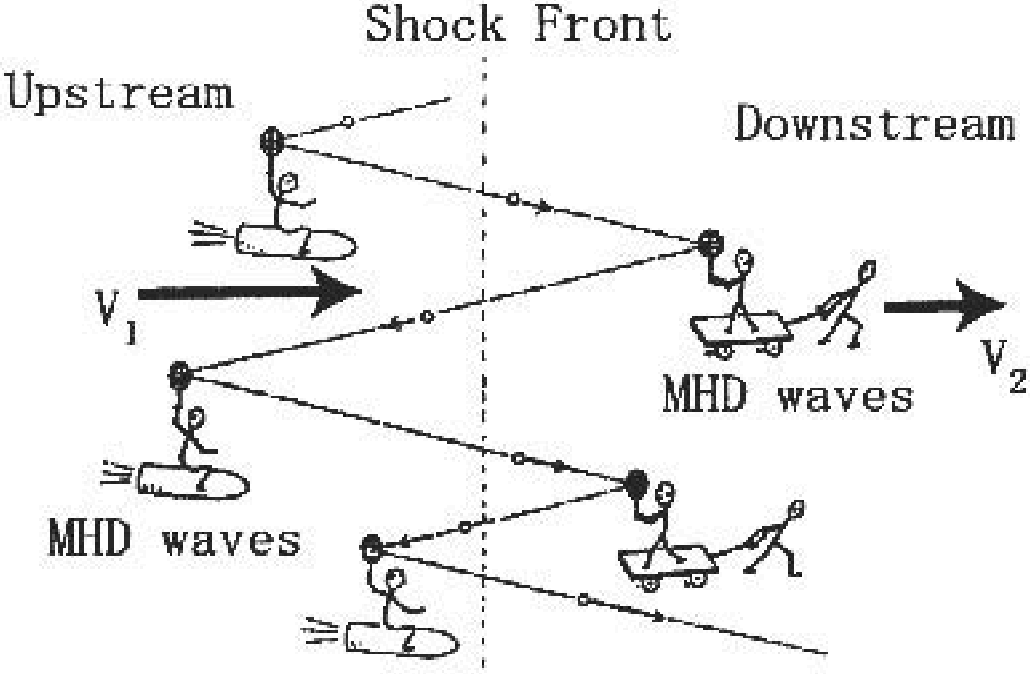
"Hidden" neutrino sources

- **Jets before GRB emission "precursor neutrinos"**
- **Choked jets (failed GRBs) "orphan neutrinos"**

high density → $f_{p\gamma} >> 1$
all CRs are damped

How are Cosmic Rays Accelerated?

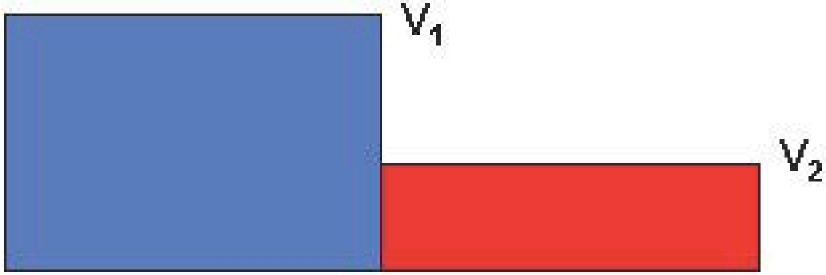
diffusive shock acceleration (Fermi mechanism)



shock=converging flows
of ionized plasma

$N(\varepsilon) \propto \varepsilon^{-s}$

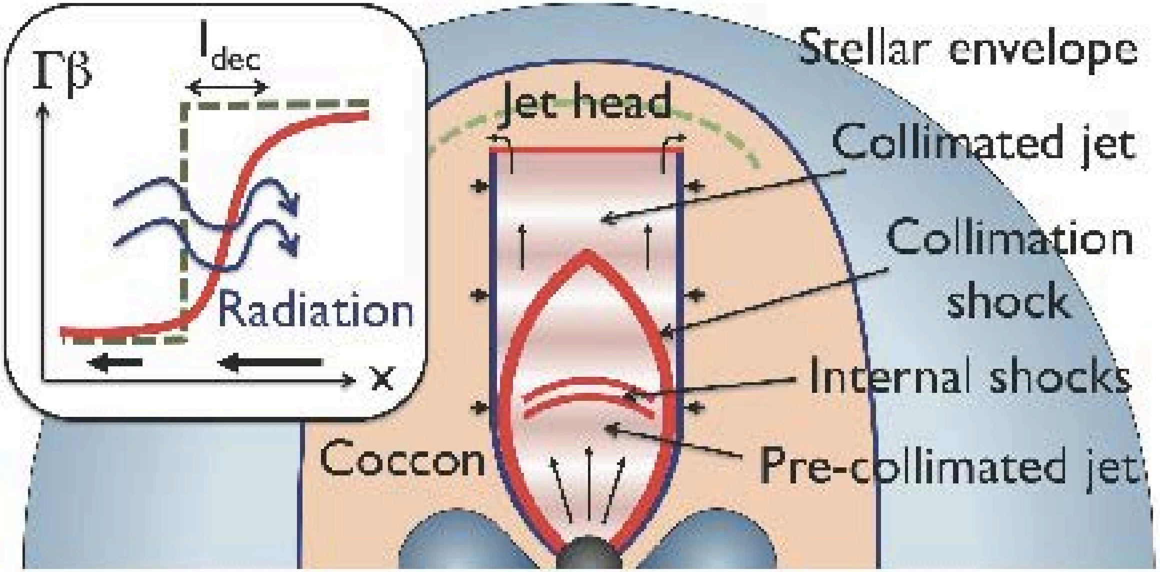
$s=(V_1/V_2+2)/(V_1/V_2-1)\sim 2$



(m.f.p.) ~ $r_L(\varepsilon_p)$ > (shock width)

More Realistic Picture

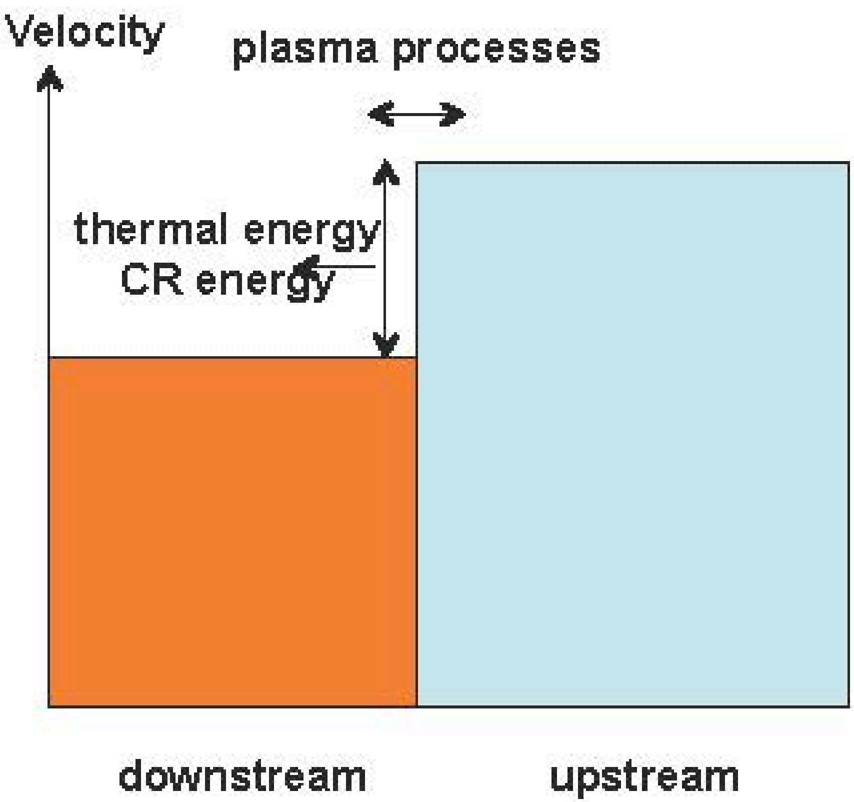
Two pieces of important physics were overlooked



1. Ballistic jets inside stars ✕
   → collimation shock & collimated jet
2. CR acceleration at collisionless shocks ○✕
   → inefficient at radiation-mediated shocks

Limitation of Shock Acceleration

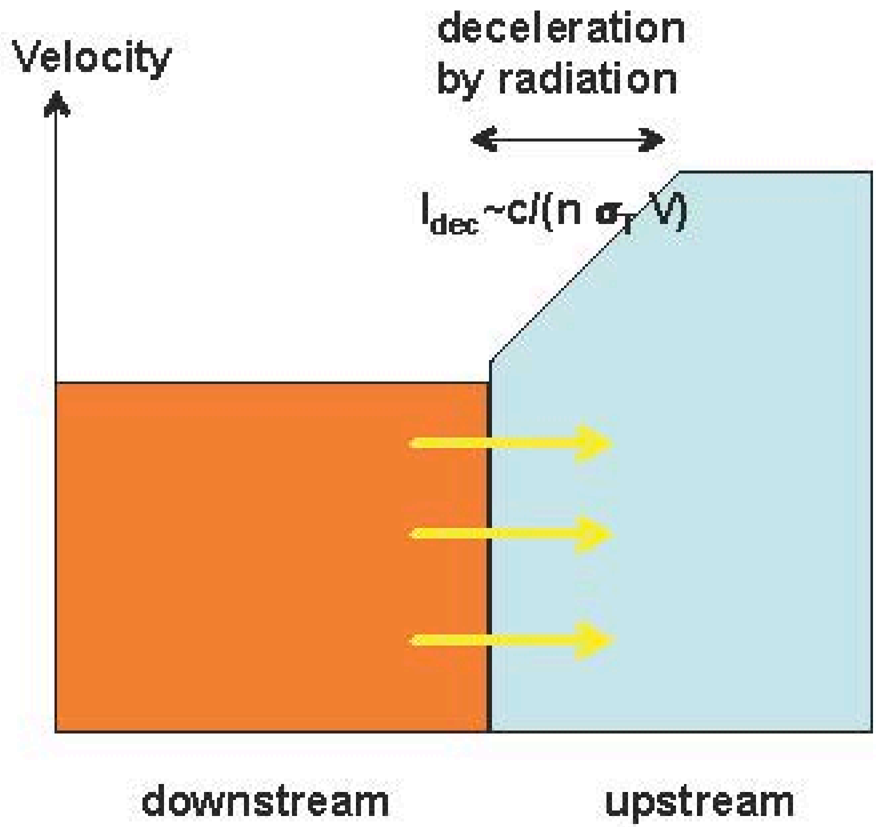
Collisionless shock



(m.f.p.) ~ $r_L(\varepsilon_p)$ > (shock width)

CR acc. possible

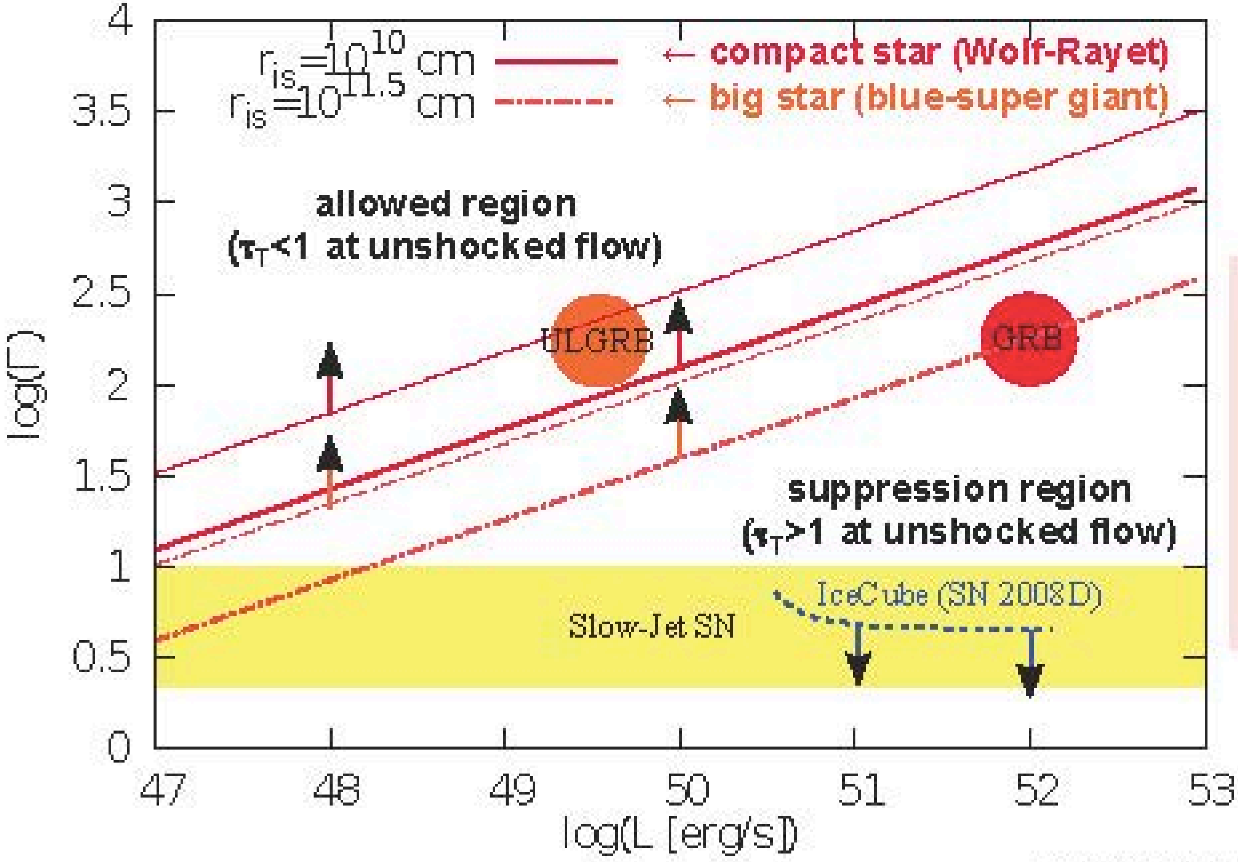
Radiation-mediated shock



(m.f.p.) ~ $r_L(\varepsilon_p)$ < (shock width)

CR acc. suppressed

"Radiation Constraints" on Non-thermal Neutrino Production



KM & Ioka 13 PRL

Thomson optical depth

$$\tau_T = n_e \sigma_T \Delta \propto L\Gamma^{-2}$$

L: kinetic luminosity

Γ: Jet Lorentz factor

- Lower-power is better
- Bigger progenitor is better

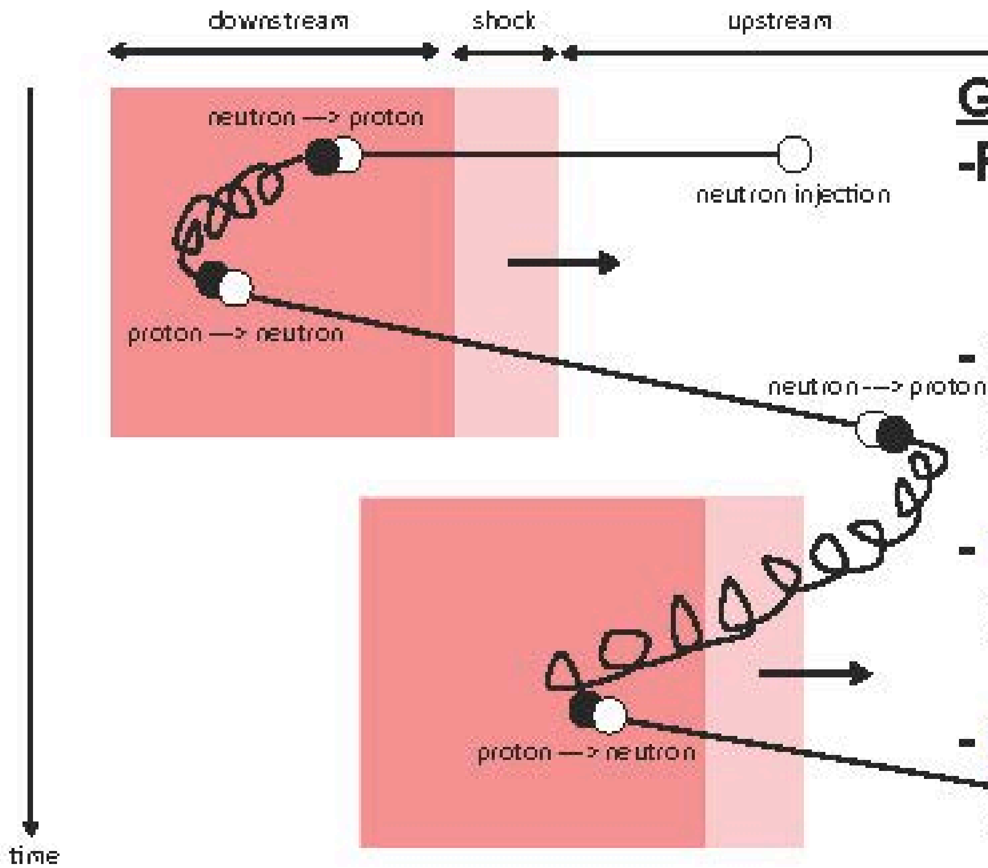
⇒

- **suppressed in typical GRBs and powerful slow-jet SNe**
- **favoring choked jets (difficulty of penetration)**

Novel Acceleration Process in Neutron-Loaded Jets

"Neutron-Proton-Converter Acceleration" (Derishev+ 03 PRD)

another Fermi acceleration mechanism without diffusion



<u>Good news</u>

-Relevance in GRB jets inside stars

(KM, Kashiyama & Meszaros 13 PRL)

- works even if radiation mediated ($\sigma_{np} < \sigma_T$)

- naturally injected (neutron m.f.p. > shock width)

- guaranteed for n-loaded flows (insensitive to plasma physics)

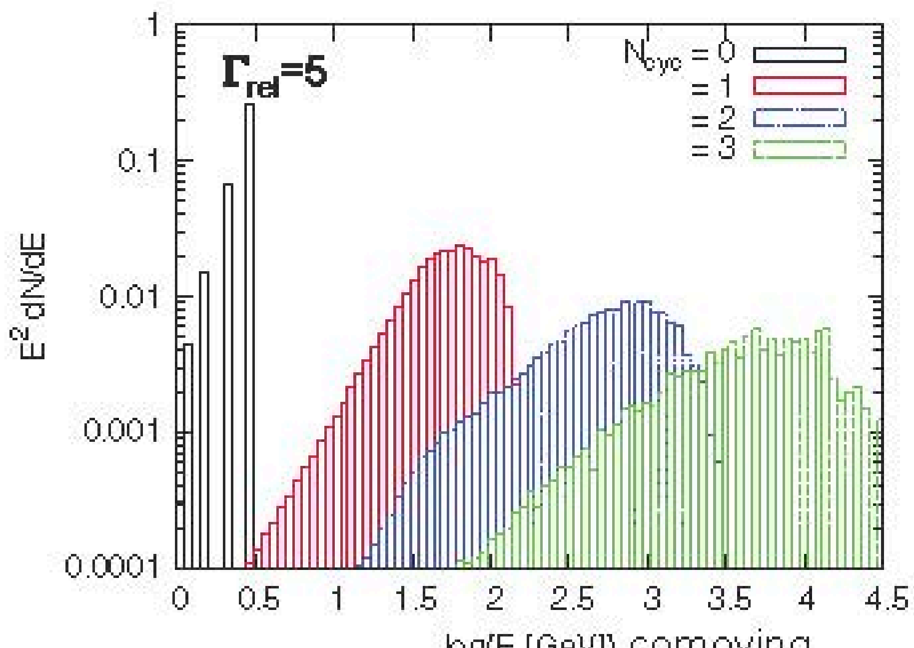
- slow process → TeV ν

NPC Acceleration: Spectra & Effects

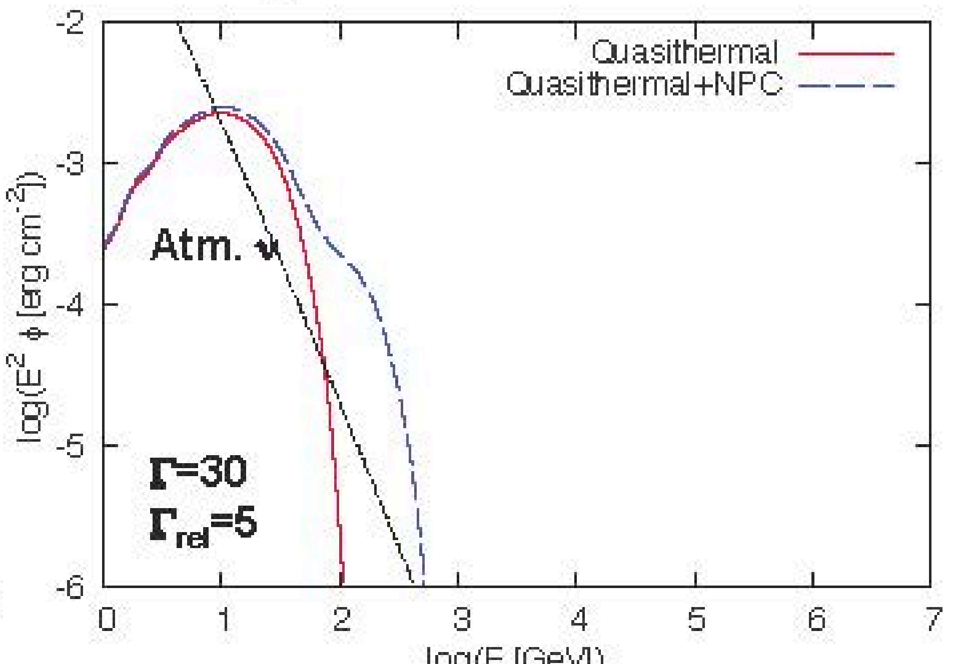
We first performed Monte Carlo simulations for test particles

- Nucleon spectra consisting of bumps rather than a power law
- >10% of incoming neutron energy can be used for NPC acc.
- Enhancement of the detectability of GeV-TeV neutrinos

Kashiyama, KM & Meszaros 13 PRL



nucleon spectra w.o. cooling



neutrino spectra

Summary

PeV neutrinos may start to be detected by IceCube

- First evidence for astrophysical high-energy neutrinos

Demystifying the origin of the diffuse neutrino flux

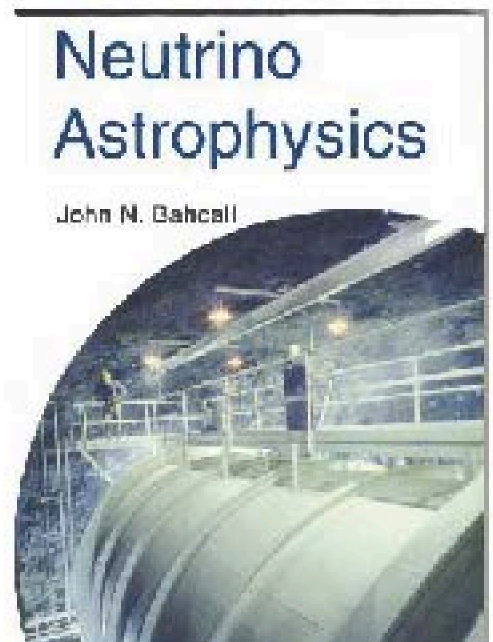
- $p\gamma$ scenarios are possible but standard models seem disfavored
- pp scenarios can be tested in the next several years by neutrino obs. (sub-PeV) and γ-ray studies (sub-TeV & >TeV)
- Relevance of sub-PeV γ-ray searches for Galactic sources

Probing cosmic explosions with multi-messenger observations

- We derived radiation constraints on TeV-PeV ν production, and low-power GRBs including choked jets are more promising
- GeV-TeV νs are promising for neutron-loaded jets

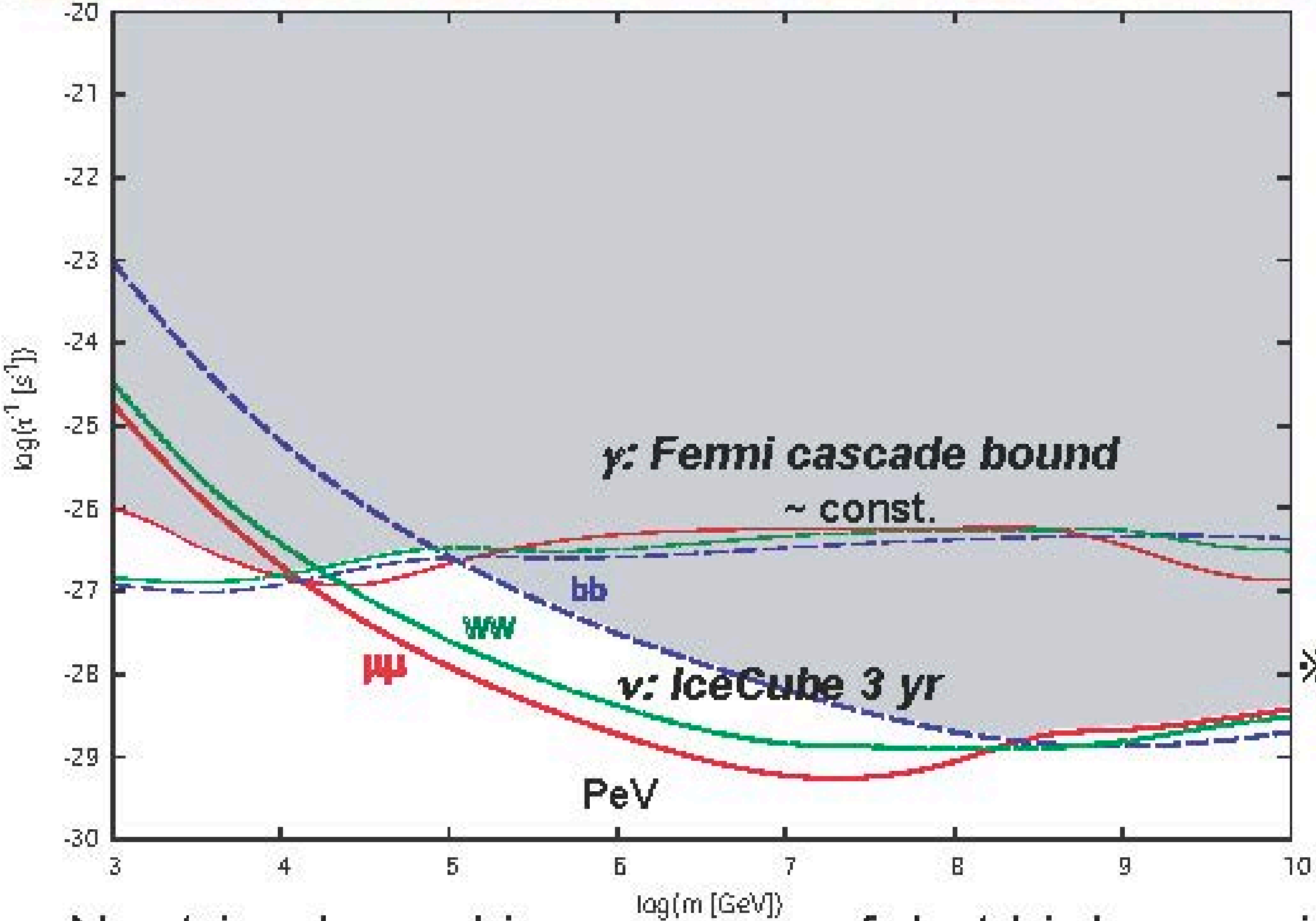
J.N. Bahcall (IAS), Neutrino Astrophysics (1989)

"The title is more of an expression of hope than a description of the book's contents....the observational horizon of neutrino astrophysics may grow ... perhaps in a time as short as one or two decades"



Backup Slides

Neutrino Constraints on Dark Matter Decay

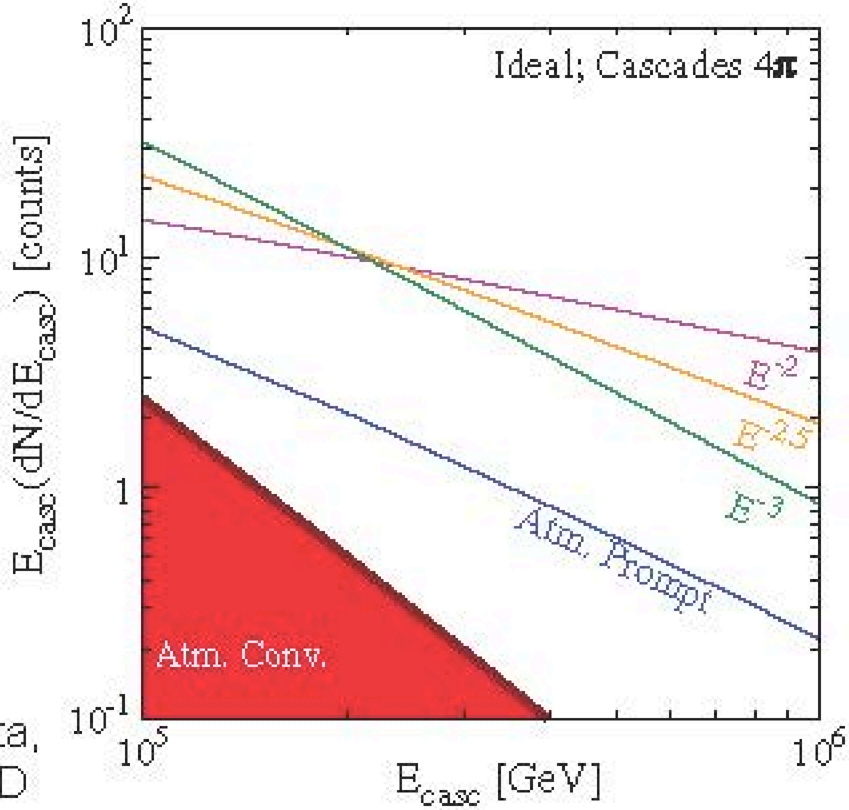


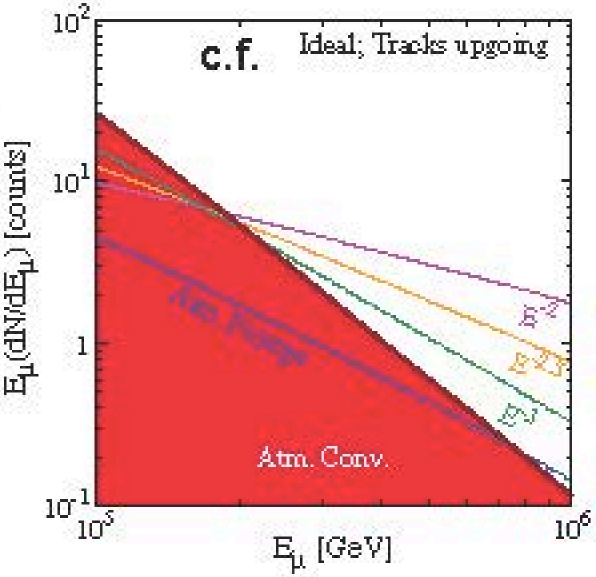
KM & Beacom 12 JCAP

※Annihilating heavy dark matter scenarios are difficult due to the unitarity bound

- Neutrino bound is very powerful at high energies
- Cascade γ-ray bound: more conservative/robust at high m_{dm}
- The dark matter scenario can be tested soon (KM+ in prep.)

Implications for Further Neutrino Studies

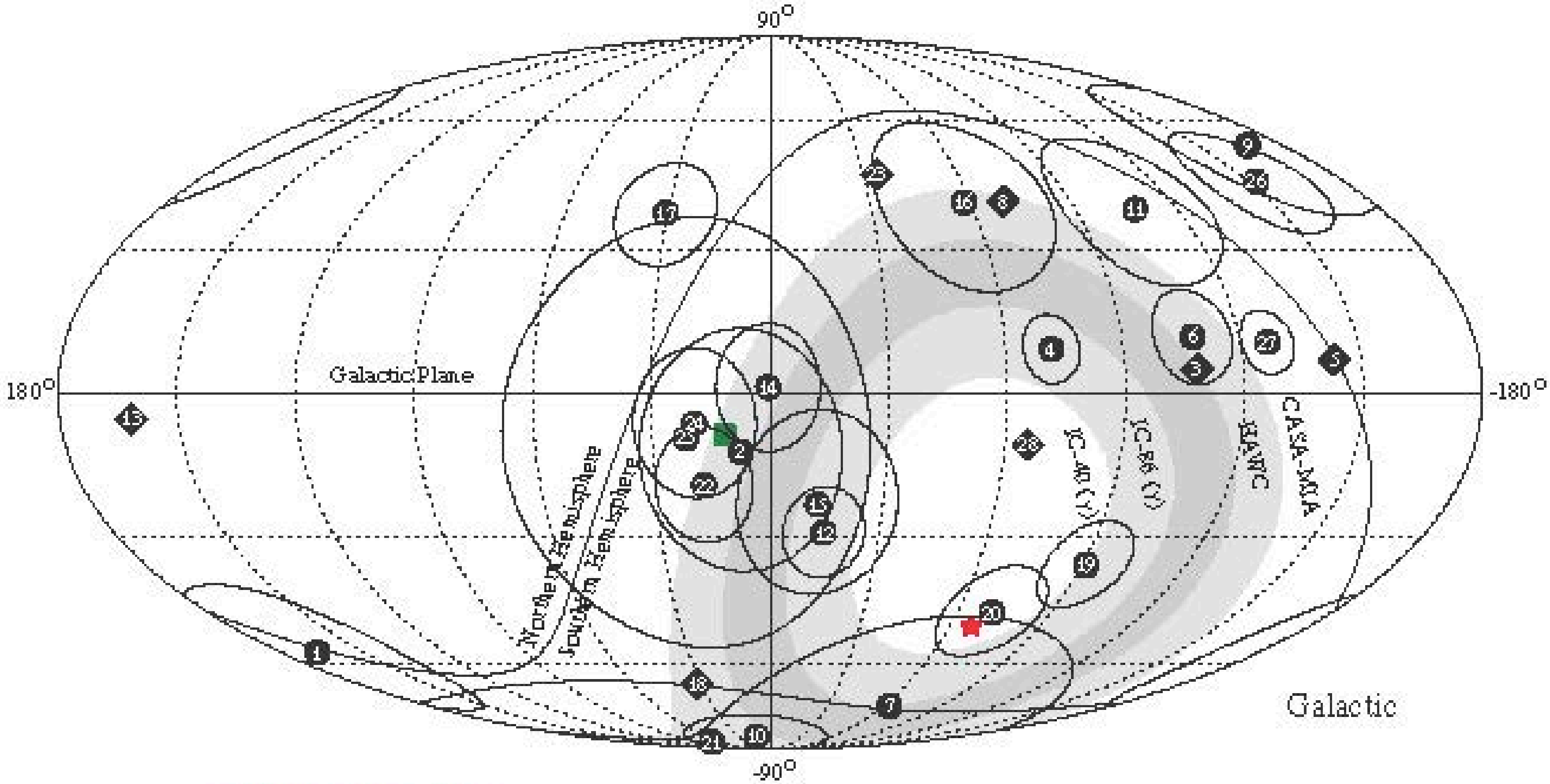




Laha, Beacom, Dasgupta, Horiuchi & KM 2013 PRD

Shower searches at lower energies offer the fastest way to distinguish between the neutrino spectra
ex. if $\Gamma > 2.3 \rightarrow$ pp scenarios will be disfavored

Q. Galactic Contributions?

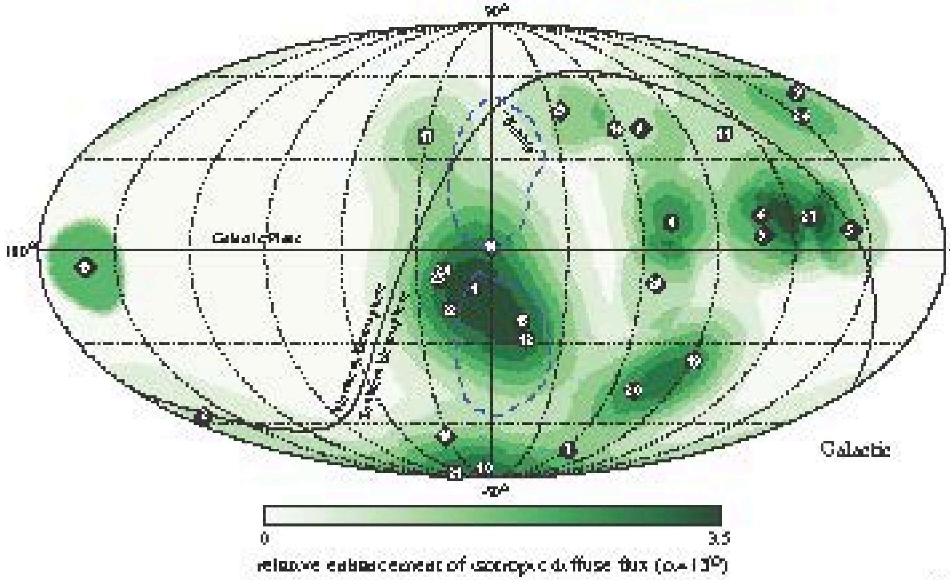


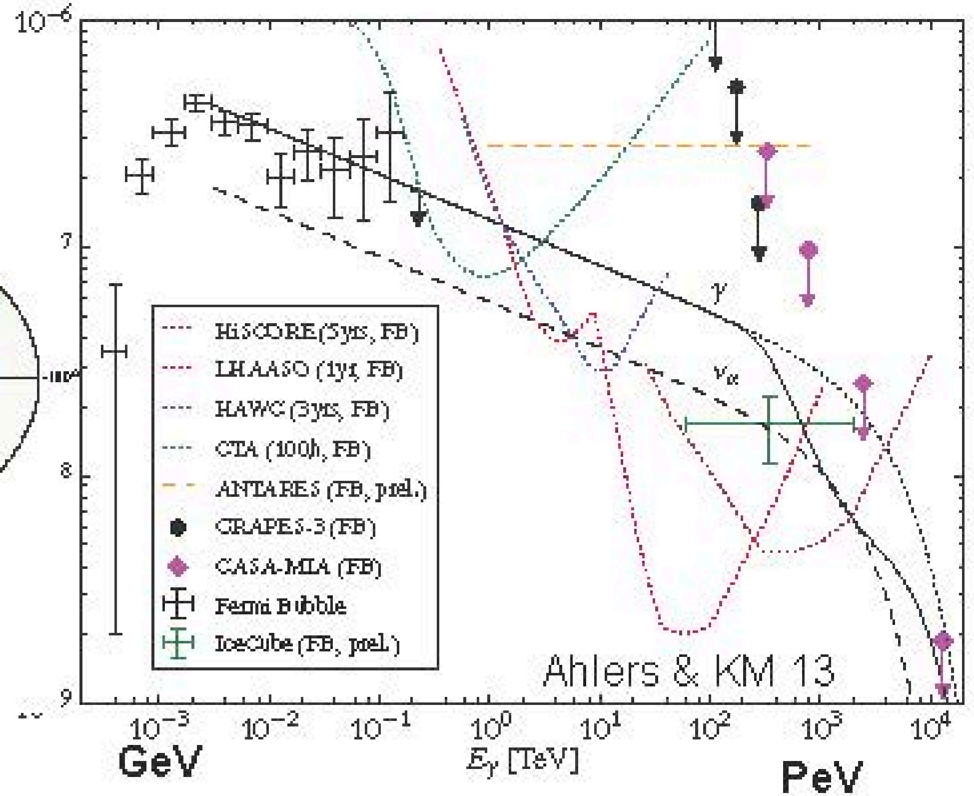
- So far, much more papers came out Galactic scenarios
- Need for PeV gamma-ray searches in the southern hemisphere

Q. Galactic Contributions?

Possibly, a fraction of the IceCube signal come from Galactic sources

example: Fermi bubbles





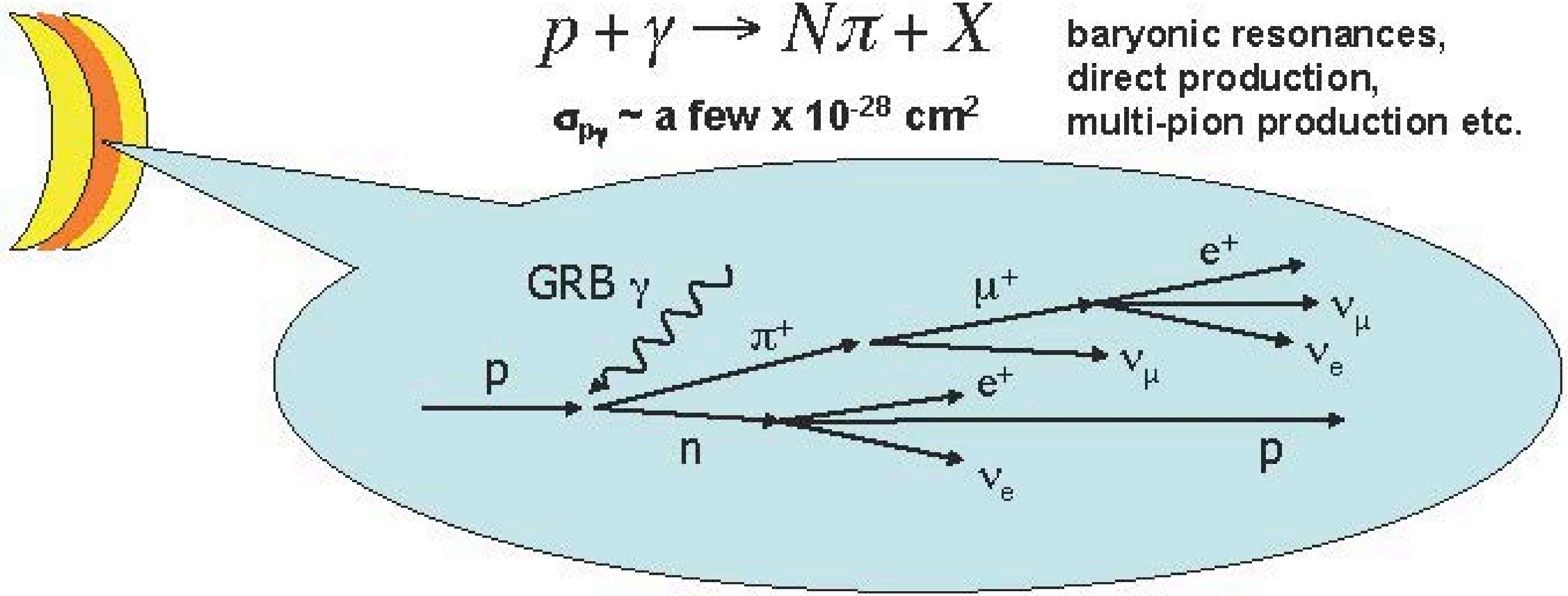
- up to 7 (among 28) can be associated w. Fermi bubbles
- consistent w. $\Gamma=2.2$ (while the cutoff is indicated by Fermi)
- should be tested by γ-ray detectors such as HAWC

Neutrino Production in the Source

$$p + \gamma \rightarrow N\pi + X$$

$\sigma_{p\gamma}$ ~ a few x 10^{-28} cm^2

baryonic resonances,
direct production,
multi-pion production etc.



at Δ-resonance ($\varepsilon_p\, \varepsilon_\gamma \sim 0.2\, \Gamma^2$ GeV^2)

$\varepsilon_\nu^{\mathbf{b}} \sim 0.05\, \varepsilon_p^{\,b} \sim 0.01$ GeV^2 $\Gamma^2/\varepsilon_{\gamma,pk} \sim$ 1 PeV (if $\varepsilon_{\gamma,pk} \sim$ 1 MeV)

Meson production efficiency (large astrophysical uncertainty)

$f_{p\gamma} \sim 0.2\, n_\gamma \sigma_{p\gamma}\, (r/\Gamma) \propto r^{-1}\,\Gamma^{-2} \propto \Gamma^{-4}\,\delta t^{-1}$ (if $r \sim \Gamma^2\, \delta t$)

Neutrino Spectra

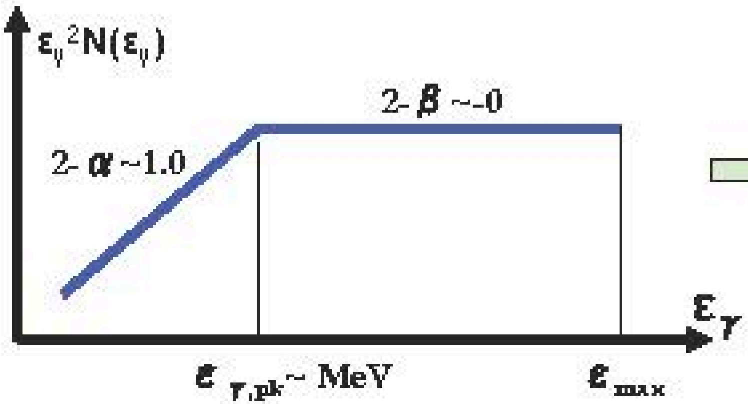
CR Spectrum (Fermi mechanism)

$N(\varepsilon_p) \propto \varepsilon_p^{-s}$ (s~2 assumed)

$E_{HECR} \equiv \varepsilon_p^2 N(\varepsilon_p) \sim E_\gamma$ (GRB-UHECR)

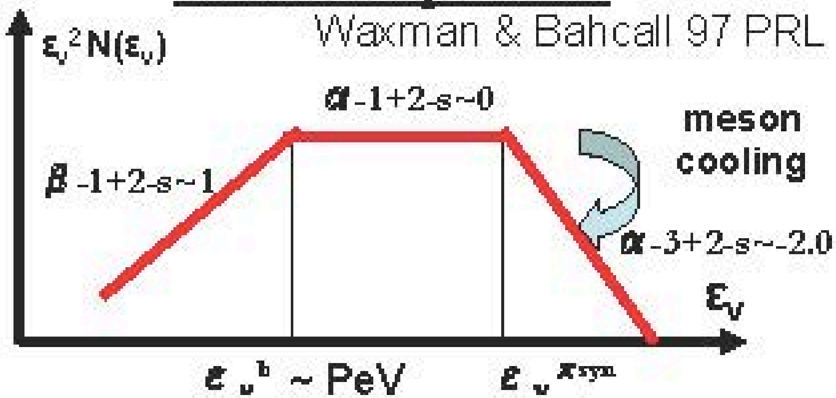
$E_{CR} = \int d\varepsilon_p \, \varepsilon_p \, N(\varepsilon_p) \sim 20 \, E_{HECR}$

Photon Spectrum (observed)



Neutrino Spectrum

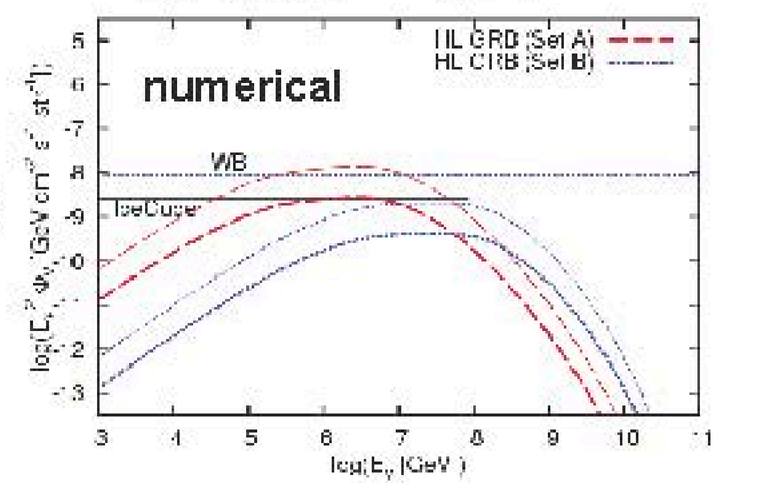
Waxman & Bahcall 97 PRL



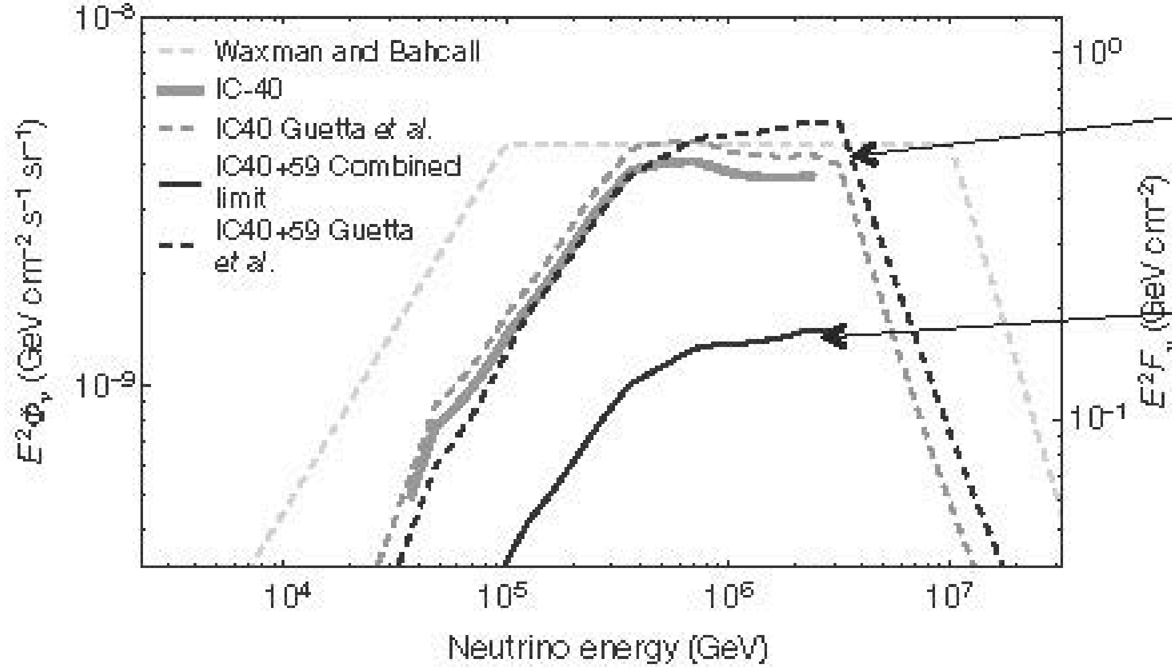
more detailed microphysics

- higher resonances & multi-pion production
- CR cooling (photomeson, photopair, syn., IC)
- muon, pion, kaon w. their cooling
- neutrino mixing

ex. KM & Nagataki 06 PRD, Baerwald+ 11 PRD



Recent IceCube Limits on Prompt ν Emission



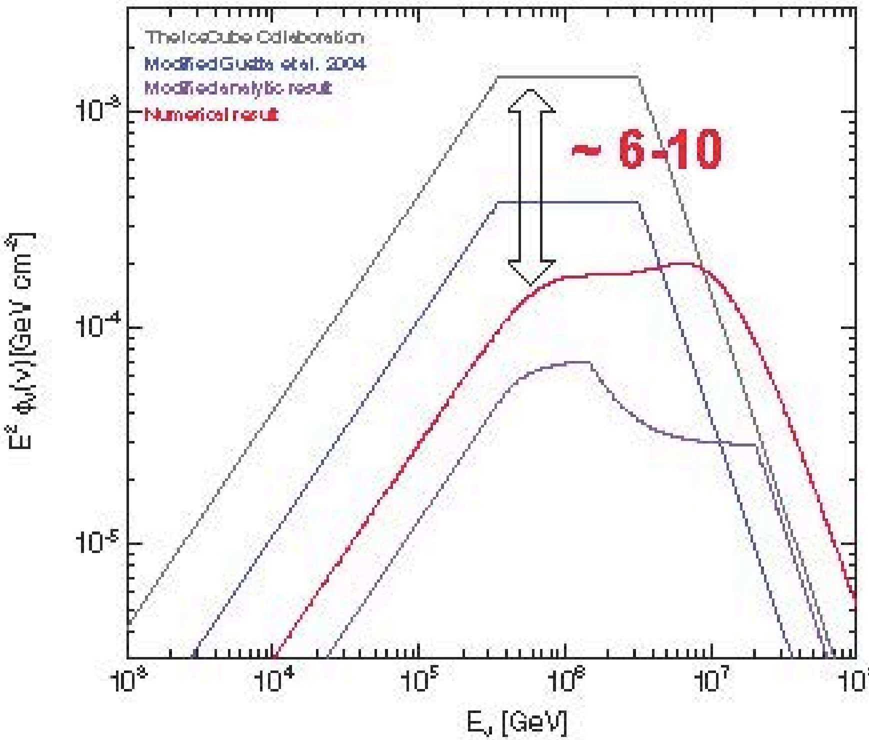
Observational limits start to be powerful but be careful

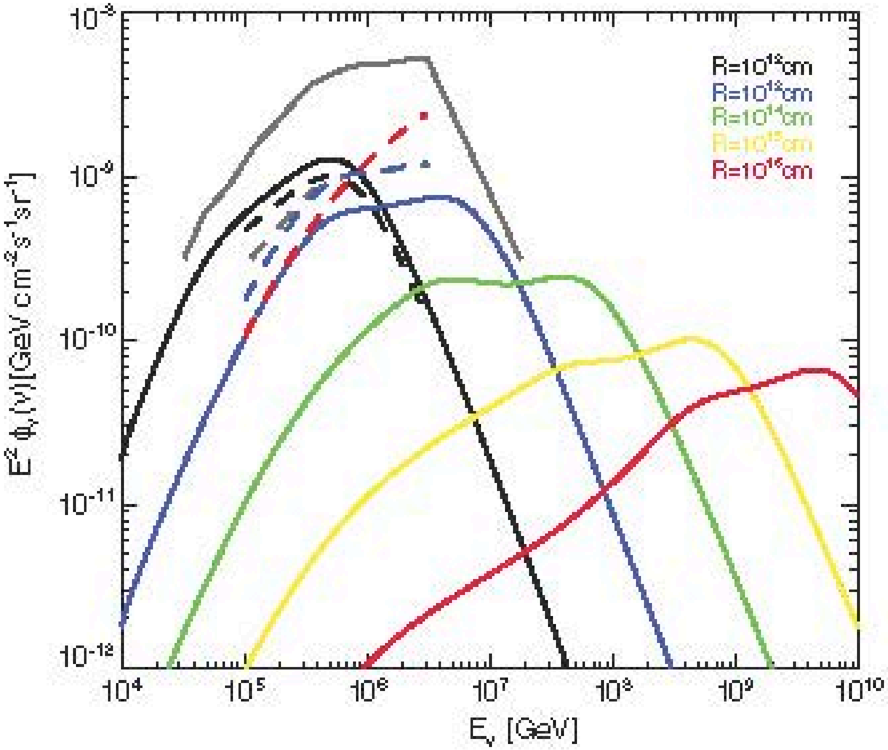
1. $f_{p\gamma}$ is energy-dependent, π-cooling → ~ 4 ↓ (Li 11, Hummer et al. 12)
2. ($\varepsilon_\gamma^2\ \phi_\gamma$ at $\varepsilon_{\gamma,pk}$) ≠ ($\int d\varepsilon_\gamma\ \varepsilon_\gamma\ \phi_\gamma$) → ~3-6 ↓ (Hummer et al. 12, He+ KM 12)
3. details (multi-π, ν mixing etc.) → ex., multi-π ~2-3 ↑ (KM & Nagataki 06)

totally different from “astrophysical” model-uncertainty in calculating $f_{p\gamma}$

※ our pre-IceCube models do not have the above problems (ex. KM & Nagataki 06)

Implications of IceCube "Stacking" Searches

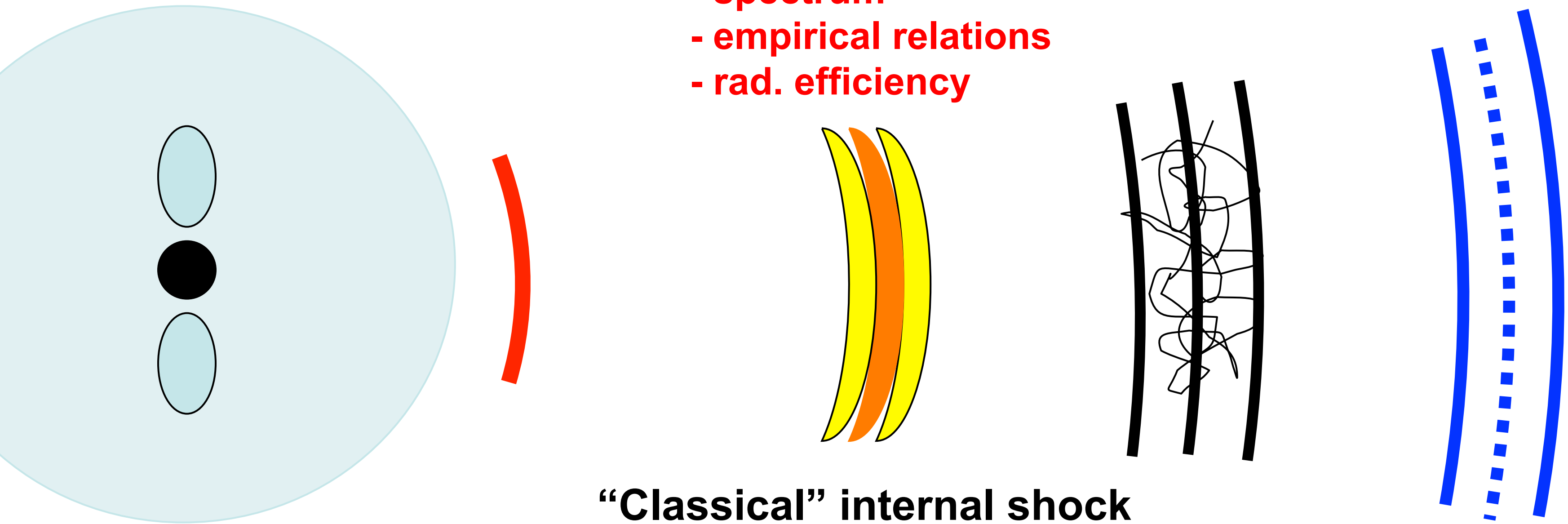


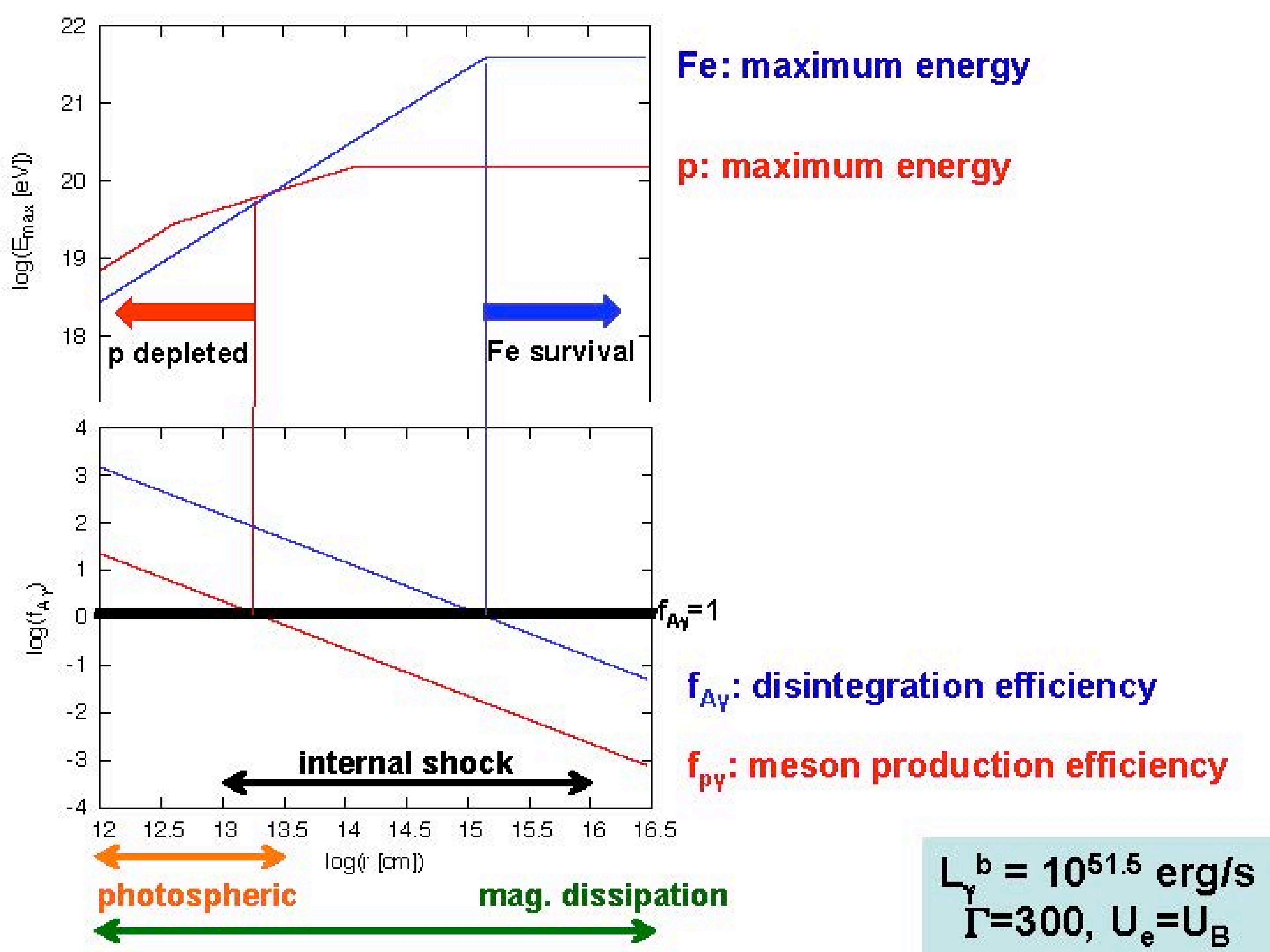


He+ KM 12 ApJ (see also Hummer et al. 12 PRL)

- **+ Not ruled out yet**
- **+ ~10 yr observations by IceCube can cover most of relevant parameter space for the GRB-UHECRp hypothesis**

Fall of Classical GRB Picture



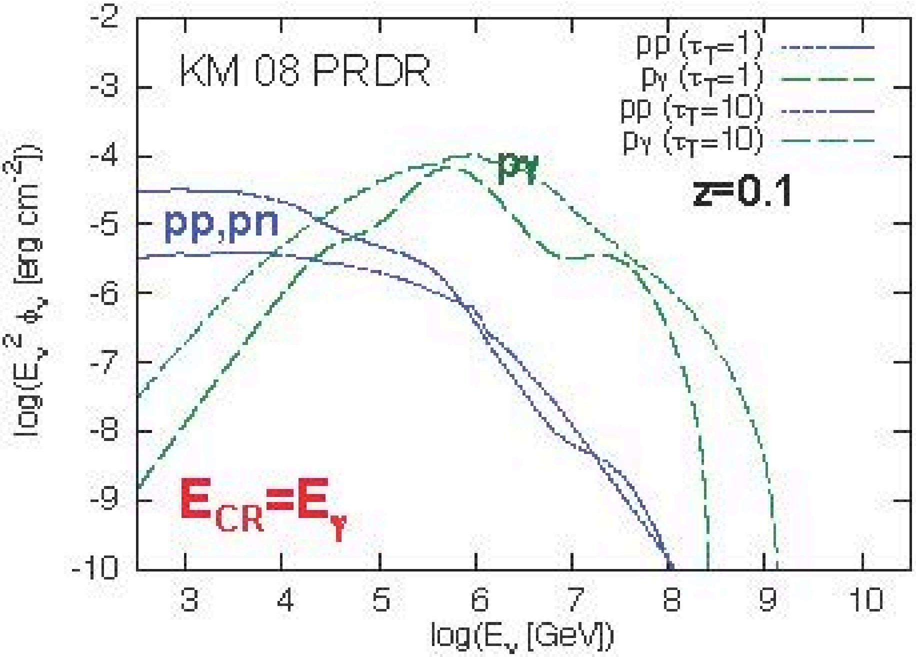


Fe: maximum energy
p: maximum energy
p depleted
Fe survival
$f_{A\gamma}=1$
$f_{A\gamma}$: disintegration efficiency
$f_{p\gamma}$: meson production efficiency
internal shock
photospheric
mag. dissipation
$\log(E_{max}$ [eV])
$\log(f_{A\gamma})$
log(r [cm])
$L_\gamma^b = 10^{51.5}$ erg/s
Γ=300, $U_e=U_B$

Model-Dependent Predictions

Dissipative photosphere

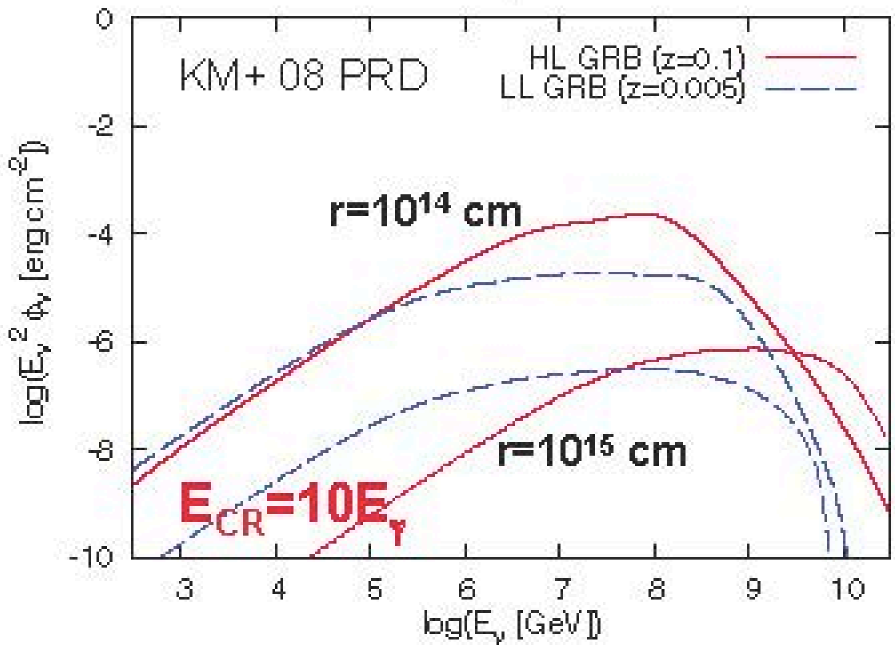
- GeV-TeV due to pp
- (UHE)CRs depleted



see also Wang & Dai 09 ApJL
Gao, Asano & Meszaros 13 JCAP

Large r models

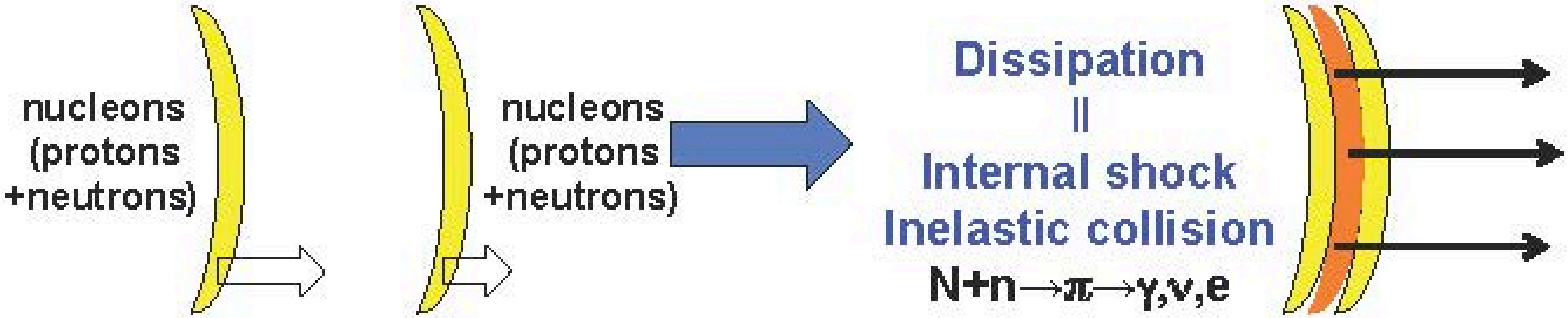
- PeV-EeV (undetectable)
- UHE "nuclei" possible



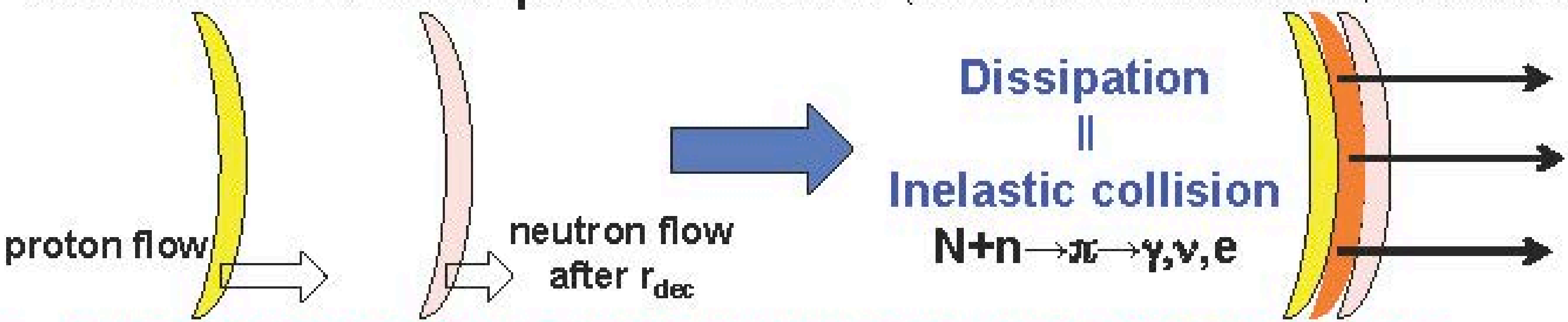
see also He et al. 12 ApJ
Zhang & Kumar 13 PRL

The Role of Neutrons at Subphotospheres: GeV Neutrinos

Collision w. compound flow (ex. Meszaros & Rees 00)

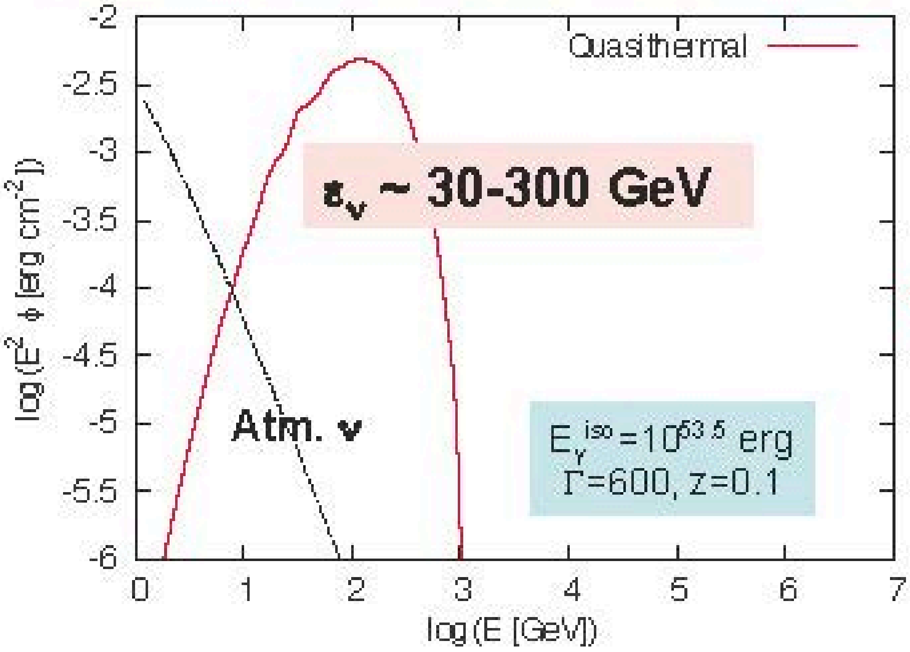


Collision w. decoupled neutrons (ex. Bahcall & Meszaros 00, Beloborodov 10)



- Quasi-thermal emission explain observed GRB spectra (via EM cascades, Coulomb heating & synchrotron)

Quasi-thermal Neutrinos are Detectable



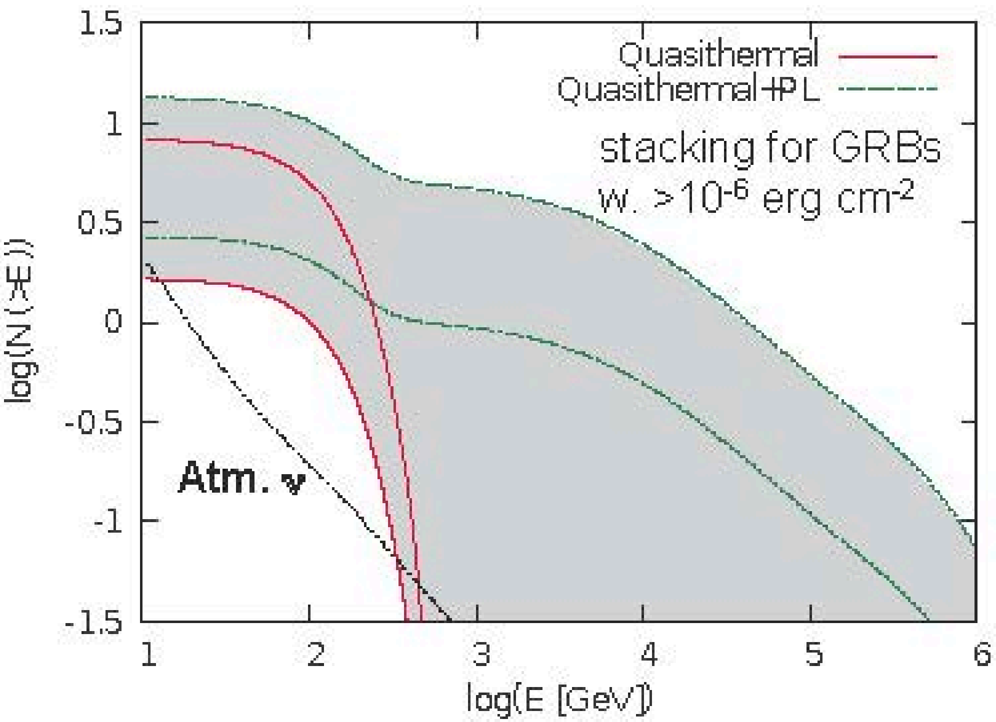
$\varepsilon_\nu \sim 0.1\, \Gamma\, \Gamma_{rel}\, m_p\, c^2$

inevitable, CRs not required

If dissipation comes from neutrons

$\varepsilon_\nu^2\, \phi_\nu \sim \varepsilon_\gamma^2\, \phi_\gamma$

- DeepCore is crucial in the 10-100 GeV range
- Stacking ~1000-2000 GRBs (~10 yr w. current satellites)

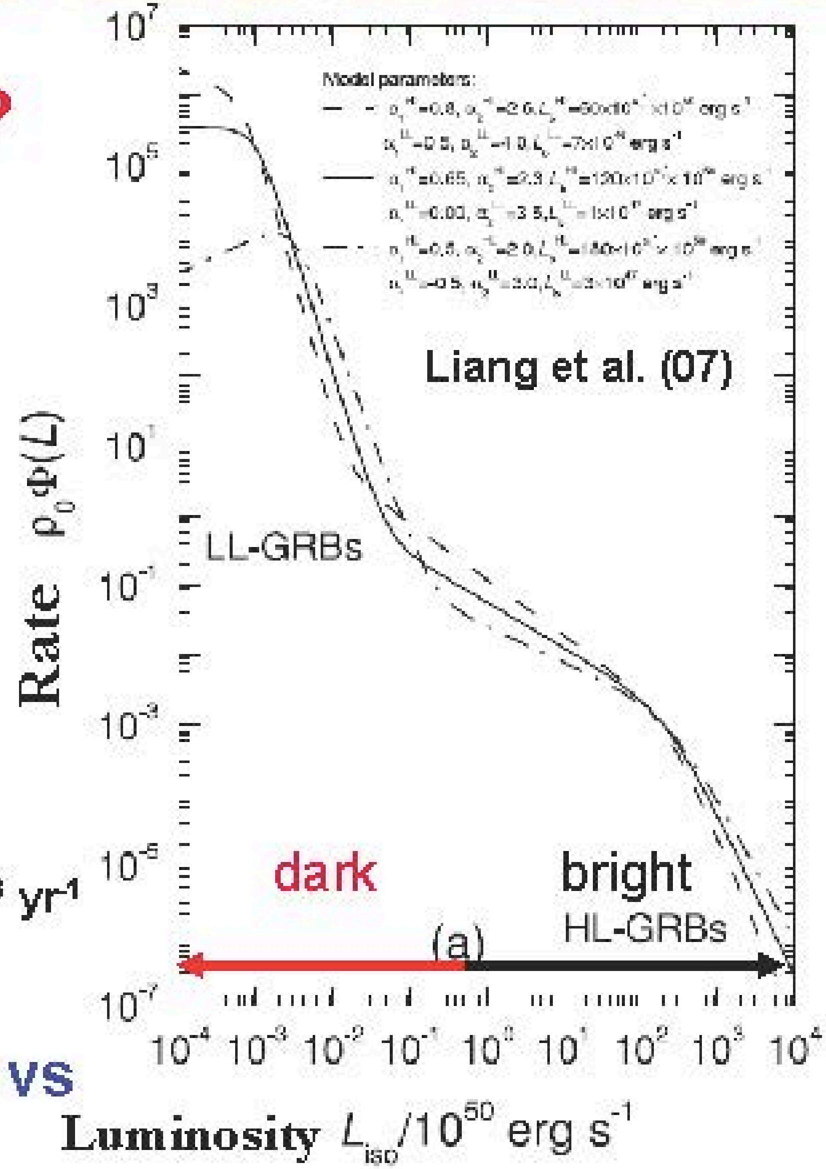


KM, Kashiyama & Meszaros 13 PRL
see also Bartos, Beloborodov+ 13 PRL

Novel Results of Swift (GRB060218)

1. Low-luminosity (LL) GRBs?

- GRB060218 (XRF060218)
  - The 2nd nearby event (~140 Mpc)
  - Associated with a SN Ic (optical)
  - Much dimmer than usual GRBs ($E_{LLGRB\gamma} \sim 10^{50}$ ergs ~ 0.001 $E_{HLGRB\gamma}$)



- LL GRBs (e.g., XRF060218, GRB980425) more frequent than HL GRBs
  local Rate ~ $10^{2\text{-}3}$ Gpc^{-3} yr^{-1} >> (0.01-1) Gpc^{-3} yr^{-1}
  (Soderberg et al. 06, Liang et al. 07 etc…)

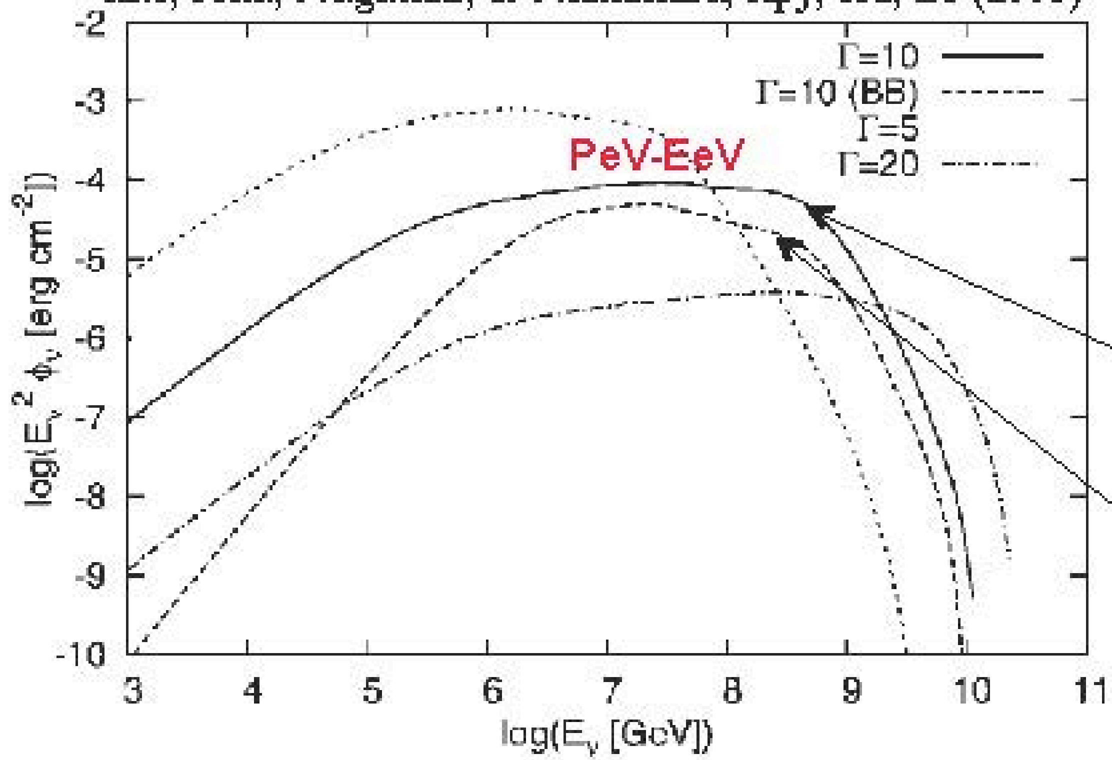
If true → contribution to HECRs & νs

Neutrinos in Jet Scenario

pγ production efficiency

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

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



$E_{CR}^{iso}/E_\gamma^{iso}$=10
U_e=U_B
D=10 Mpc

If Γ=10 w. prompt emission
→ # of μs ~ 1-2
→ optical follow-up!

If Γ=10 w. thermal X rays
(stellar shock breakout or cocoon)
→ # of μs ~ 0.1-0.2

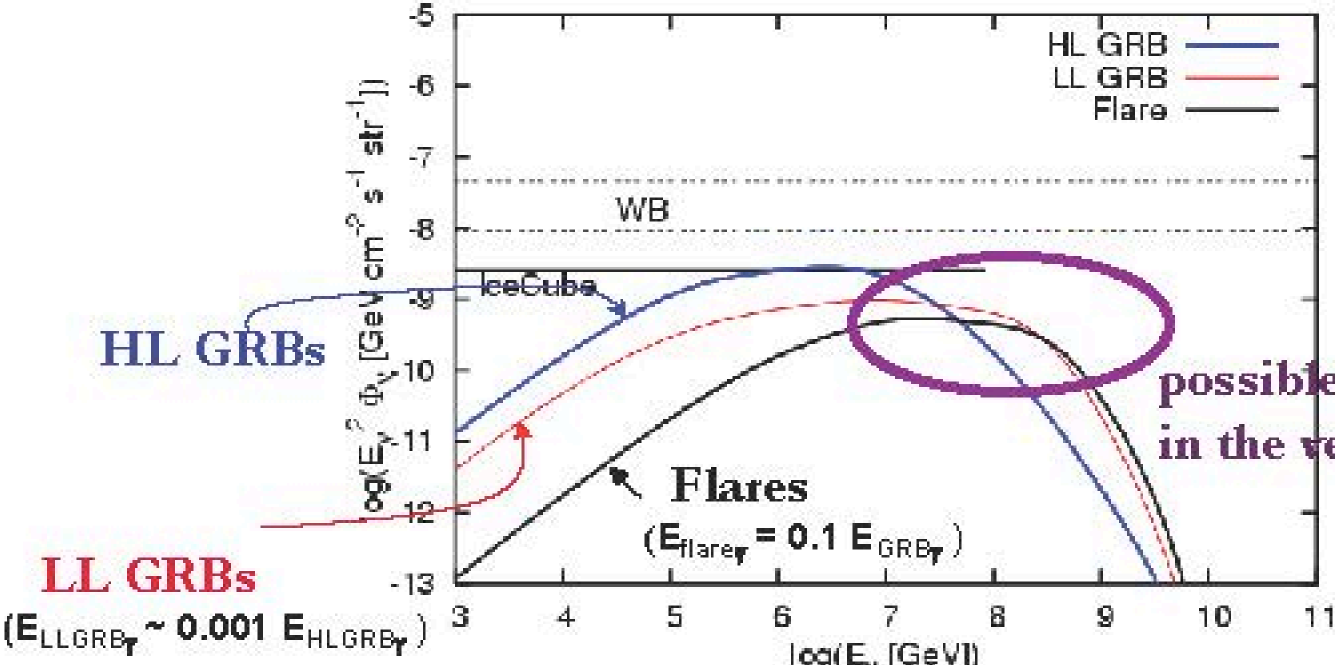
※LL GRBs accompanying relativistic SNe may produce UHECRs

KM+ 06 ApJ (energetics), Wang+ 07 PRD (ext. free exp. shock), KM + 08 PRD (int. or ext. dec. shock)

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



Baryon loading
E_{HECR} ~ 0.5 E_γ

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

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

<u>Approaches to GRBs through high-energy neutrinos</u>

Flares → potentially more baryon-rich and efficient neutrino emitters

LL GRBs → possible indicators of SNe followed by opt. telescopes