"APCTP Focus Program on Recent Developments in Neutrino Physics and Astroparticle Physics (In memory of Prof. Benjamin W. Lee)"

High Energy Neutrino Astronomy and Gamma-Ray Bursts

Yukawa Institute for Theoretical Astrophysics
ShigeHiro Nagataki

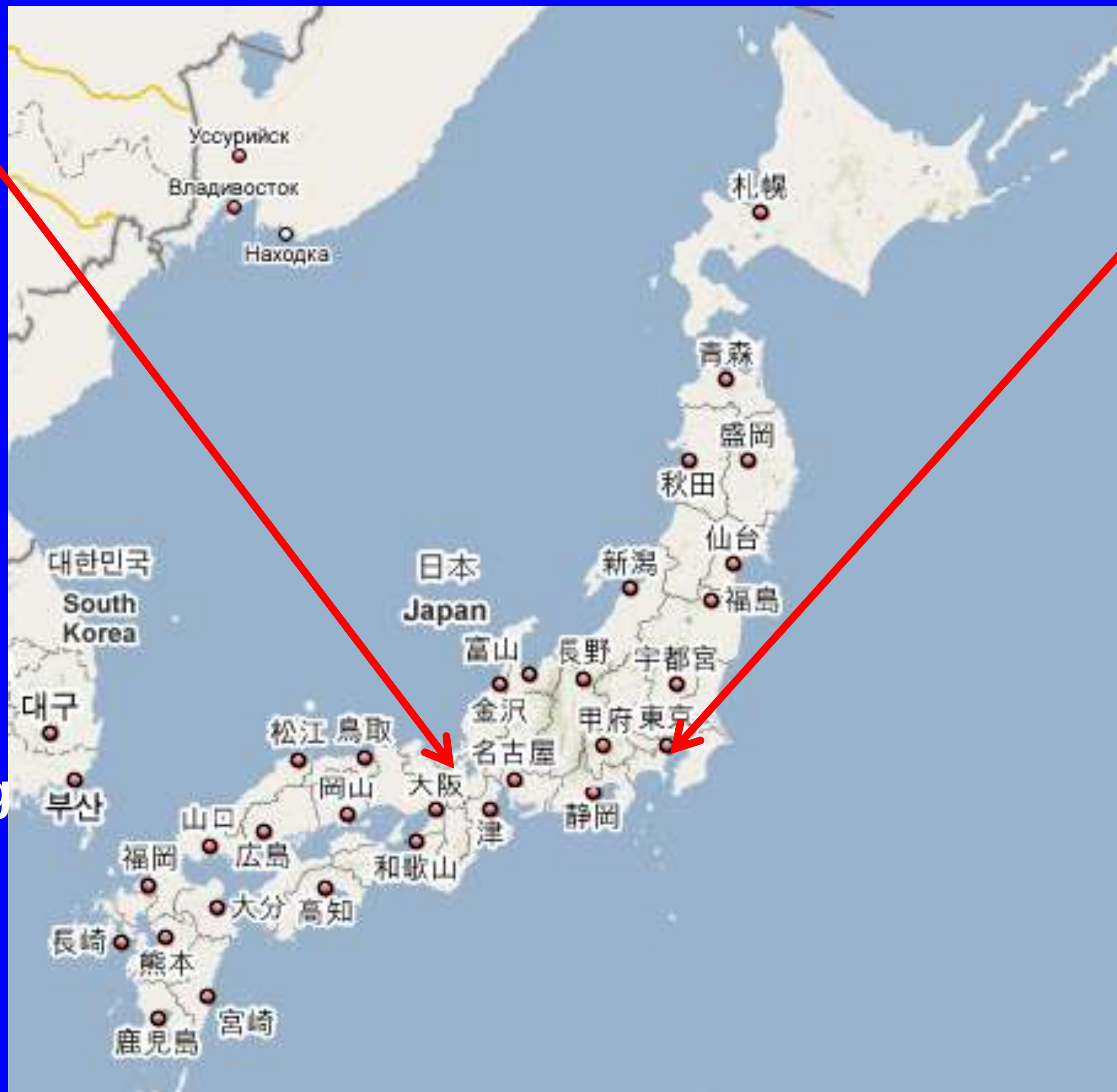
23rd June 2009, APCTP, Korea

From Tokyo to Kyoto.

Kyoto
京都

5years ago,
I have moved
To Kyoto
As an
Associate
Professor
Of Yukawa
Institute,
Kyoto Univ.

I was a visiting
Scholar of
Stanford Univ.
(KIPAC).



Tokyo
東京

I was born
And grew
Up here.

I was a
Graduate
Student,
PosDoc,
and
assistant
Professor
Of the Univ.
Of Tokyo.


靜御前

International Conference of GRB in Kyoto


- April 19-23 (2010).
- International Advisory Committee：
  G. Chincarini, J.Fynbo, N.Gehrel, C. Kouveliotou
- SOC Chair: Nobuyuki Kawai, LOC Chair: S.N.
- Kyoto is a beautiful city and has a long history.
- Please visit Kyoto and enjoy the conference!


My Name is Shigehiro Nagataki.

Family **Given**
Nagataki **Shigehiro**
長瀧 **重博**

Just call me HIRO!
Thank You !!

- Overview

Why Neutrinos?

- Cross section of neutrino interactions is very small (only weak interactions, no electric charge).
- Neutrinos come straightly from their sources. (c.f. Cosmic Rays (charged particles) in magnetic fields)
- Neutrinos bring information of the sources even if they are optically thick (ex. MeV neutrinos from a supernova core).
- Very High Energy neutrinos (TeV-PeV) can be evidence of hadron accelerations.
- Anyway, new window should give us a new picture of the universe!

Neutrinos can bring information on high-z, high-energy objects (1)

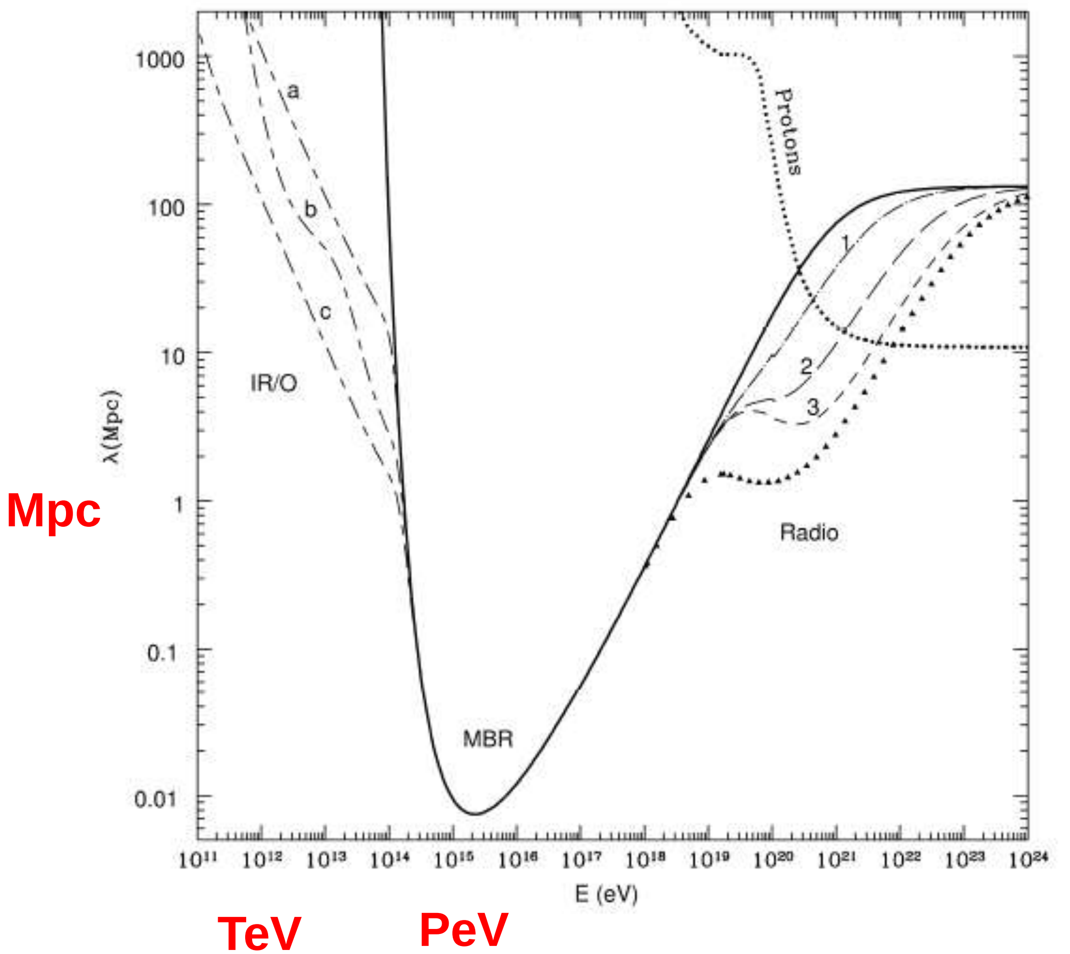


Figure 8. – Mean free path as a function of the photon energy [37].

Mean free path of photons Angelis+07

Mean free path of Very High Energy (VHE) Photons is much Less than the cosmological Distance (〜3000Mpc).

On the other hand, mean free Path of VHE neutrinos is longer than cosmological distance.

Neutrinos can bring information on high-z, high-energy objects (2)

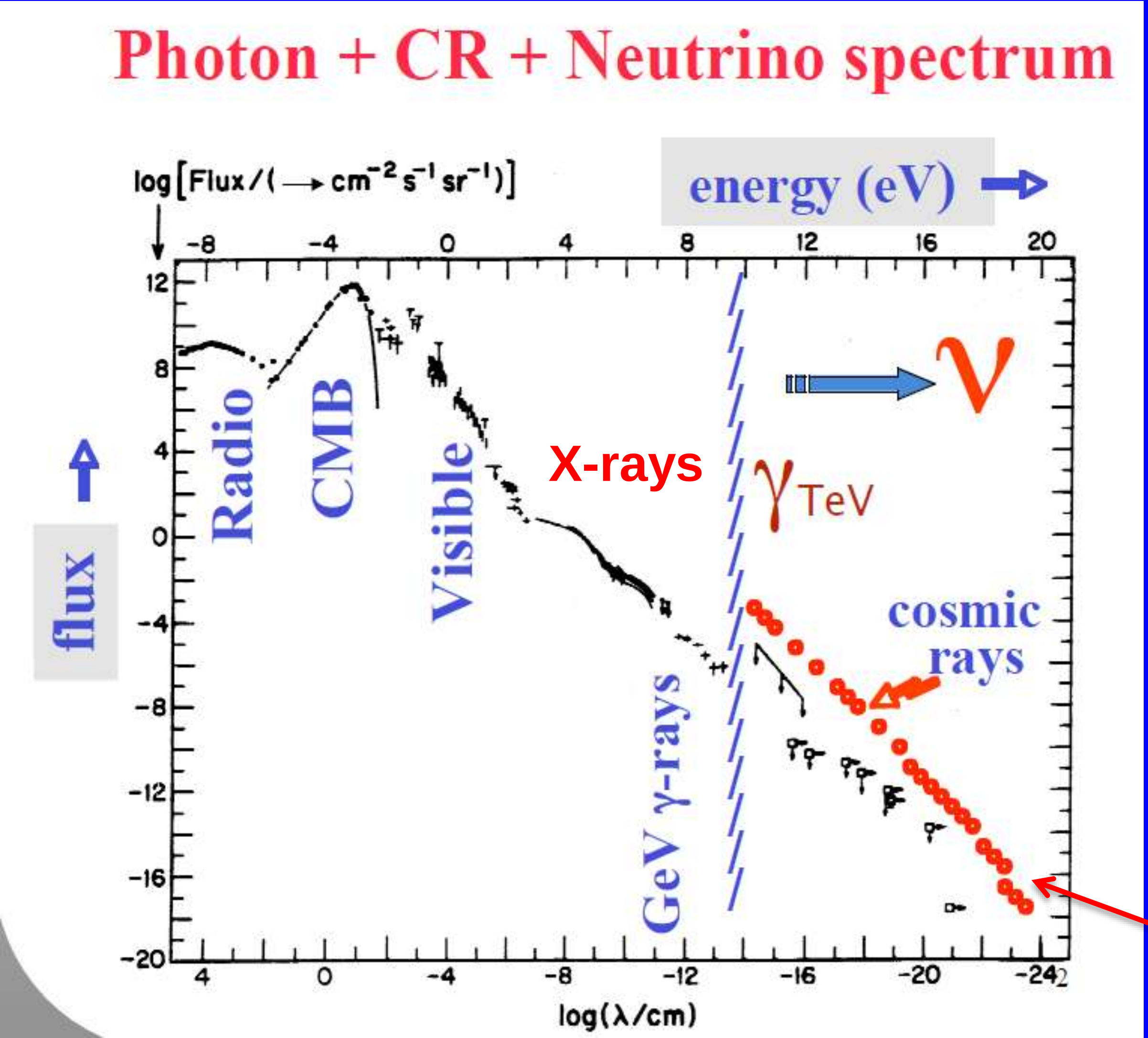


Figure From P. Meszaros

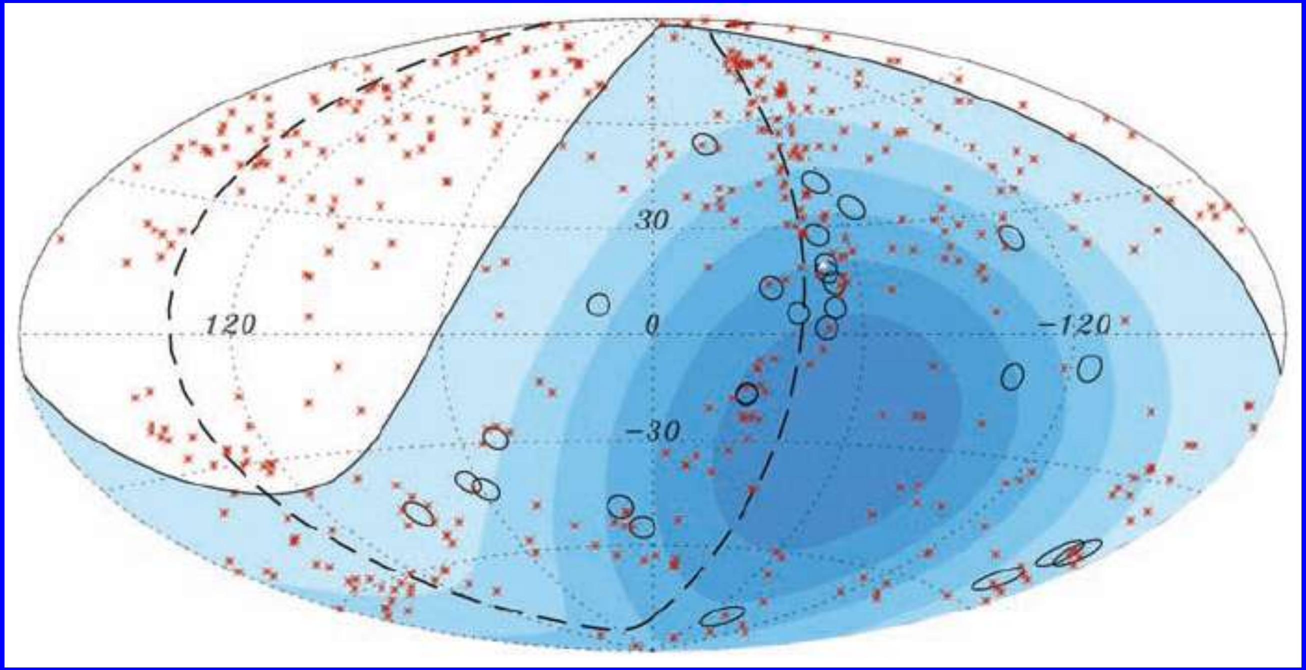
Only neutrinos (and Gravitational waves) with Energy higher than TeV Can propagate cosmological distance.

Of course, we can observe Nearby, high-energy Objects by neutrinos, too.

UHECRs

Neutrinos come straightly from their sources

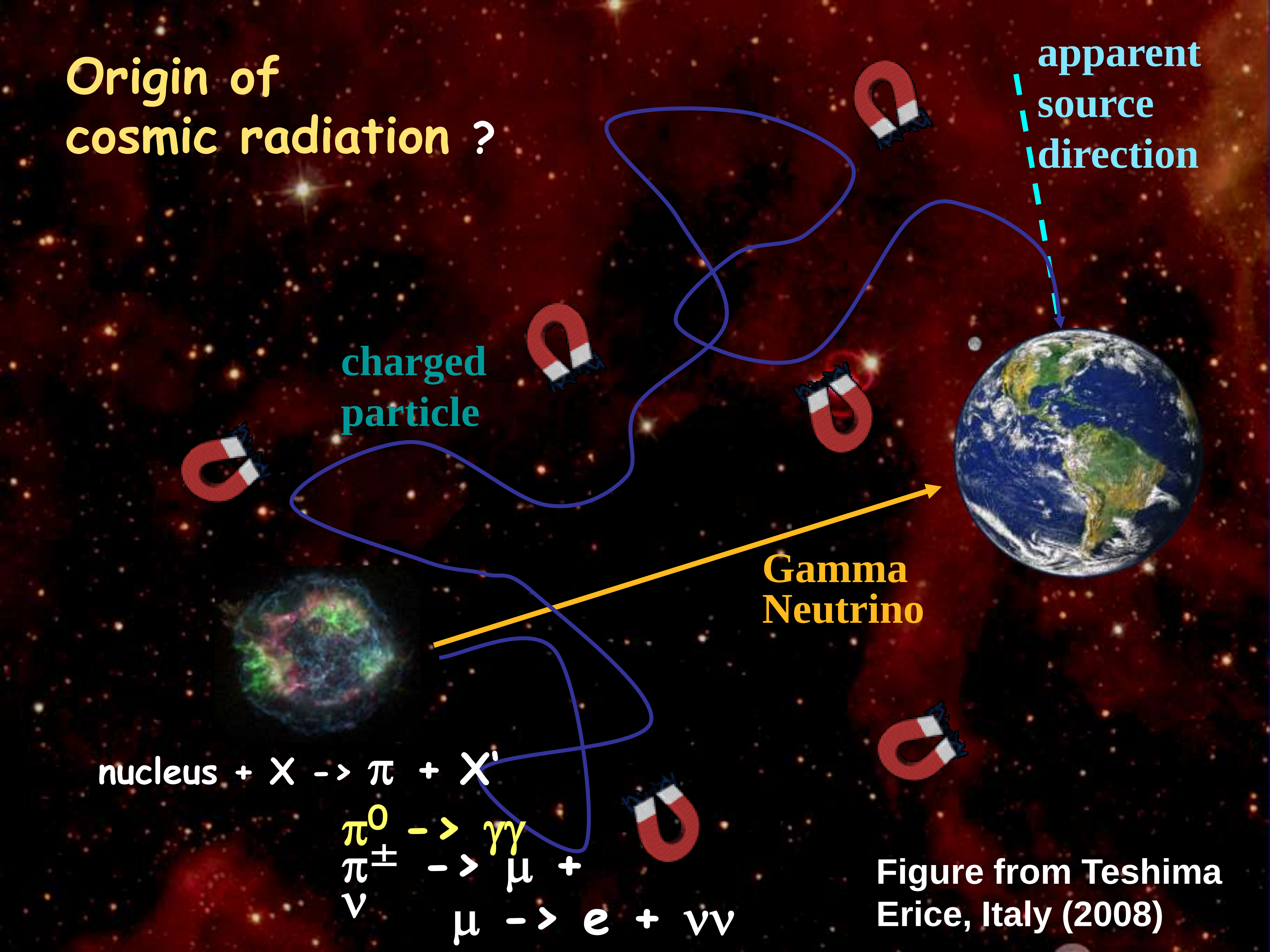
(Pierre Auger Collaboration 2007)



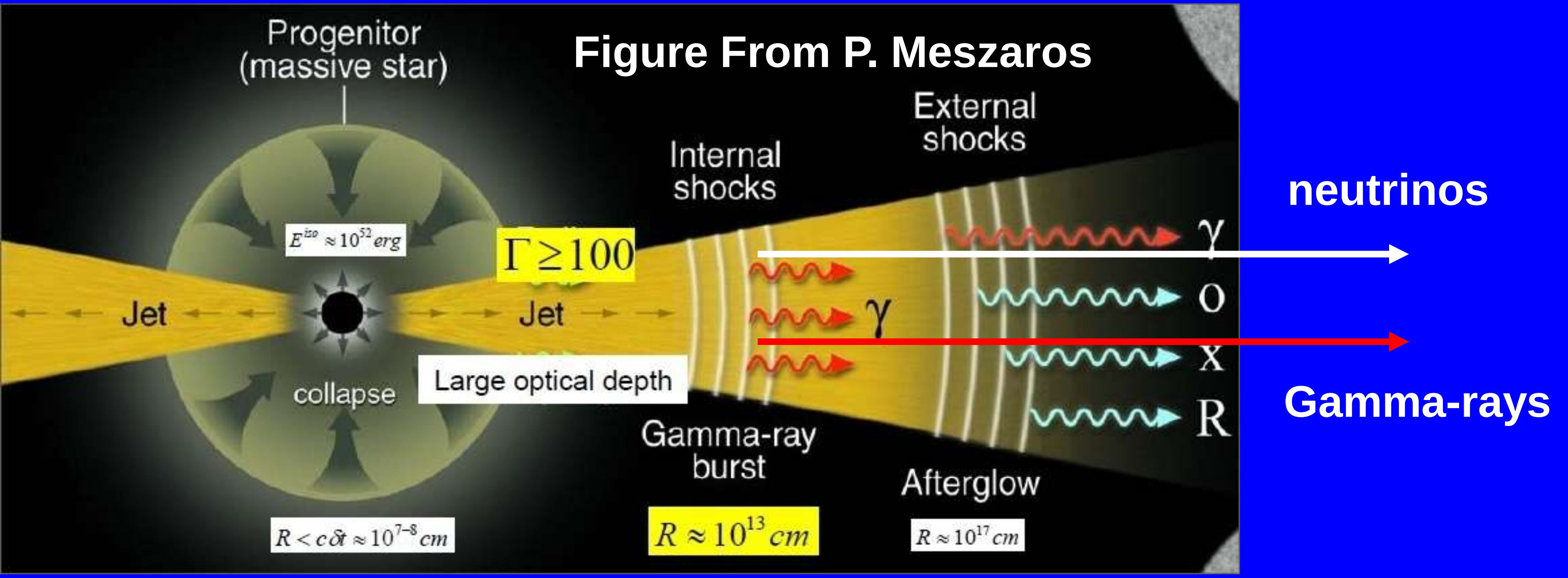
- Correlation with AGN?
  E>57EeV, z<0.018, δ=3.1º **27events**
- Correlation with Super-Galactic Plane?
- Some events came from Cen A?

See also HiRes Results.
e,g, Abbasi+ 08

Source identification would be simpler if UHECRs come straightly from their sources.


Origin of cosmic radiation ?
apparent source direction
charged particle
Gamma
Neutrino
nucleus + X -> π + X'
π0 -> γγ
π± -> μ + ν
μ -> e + νν
Figure from Teshima Erice, Italy (2008)

Neutrinos come straightly from their sources with almost speed of light



For example, VHE neutrinos from GRBs should be spatially and timely Correlated with GRBs.

Neutrinos from optically thick object

- Neutrinos can bring information of the sources even if they are optically thick.

Examples:

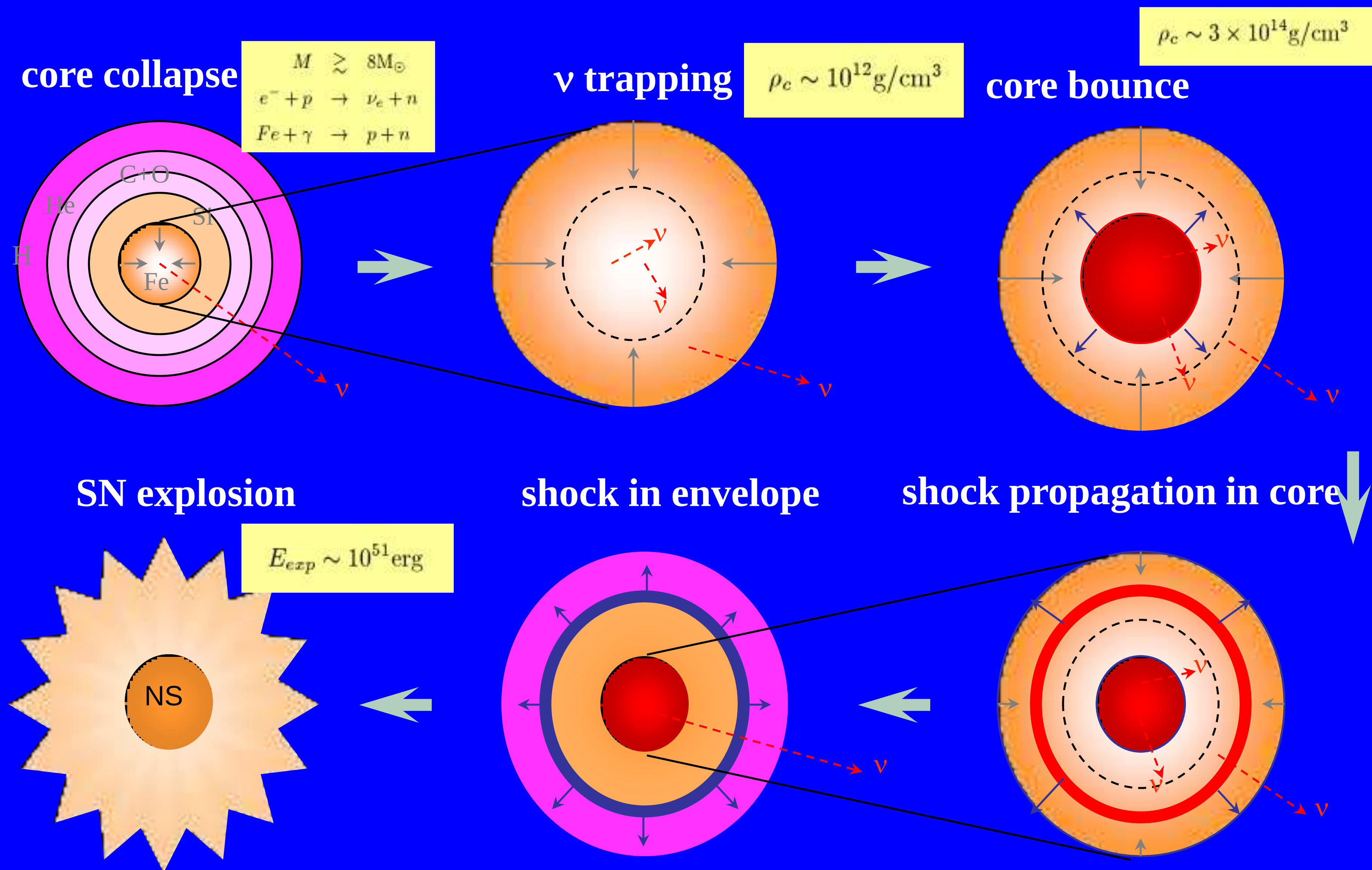
MeV neutrinos from a supernova (and GRB) core.

GeV neutrinos from a corked GRB jet.

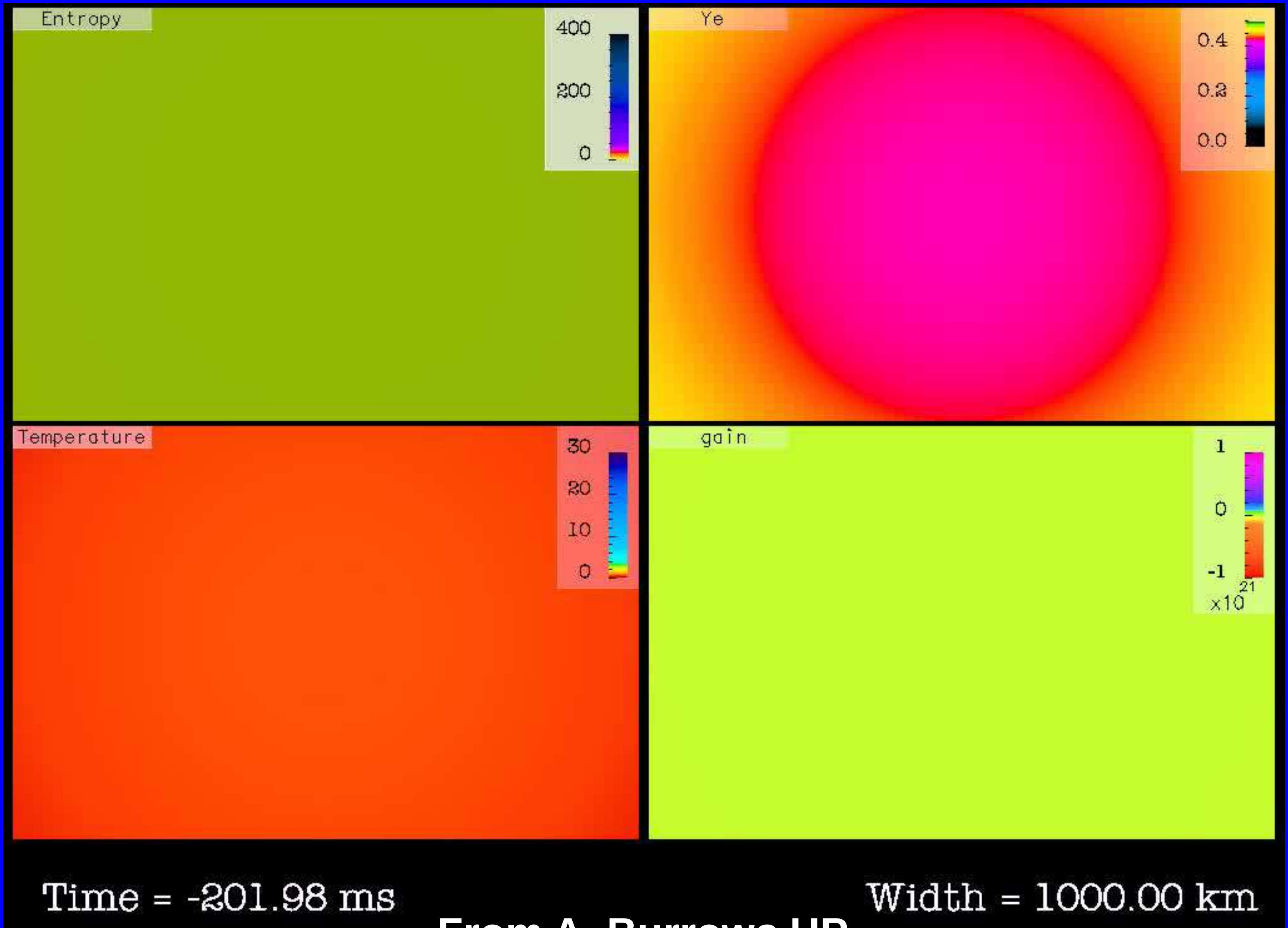
TeV neutrinos from a core of AGNs.

Schematic Picture of Core-Collapse Supernova

We can not see the central engine by photons



Dynamics of SN engine will be seen only by neutrinos and gravitational wave



From A. Burrows HP

Very High Energy neutrinos can be evidence of hadron accelerations

- Leptons and photons cannot produce VHE neutrinos efficiently.
- Flux and spectrum of neutrinos are similar to photons that are produced from pion decays.

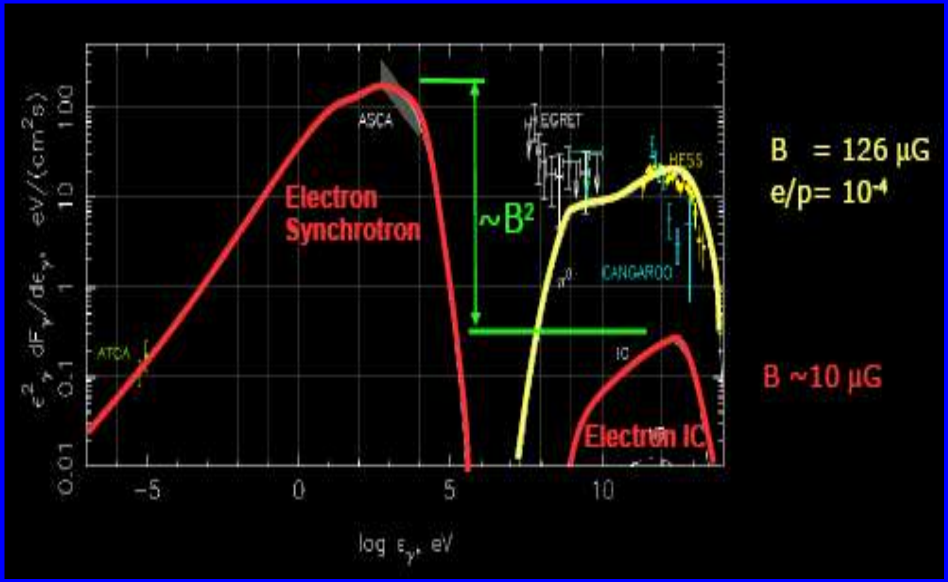
$$p + \gamma \to \Delta \to n + \pi^{+} \quad \kappa_p \sim 0.2$$

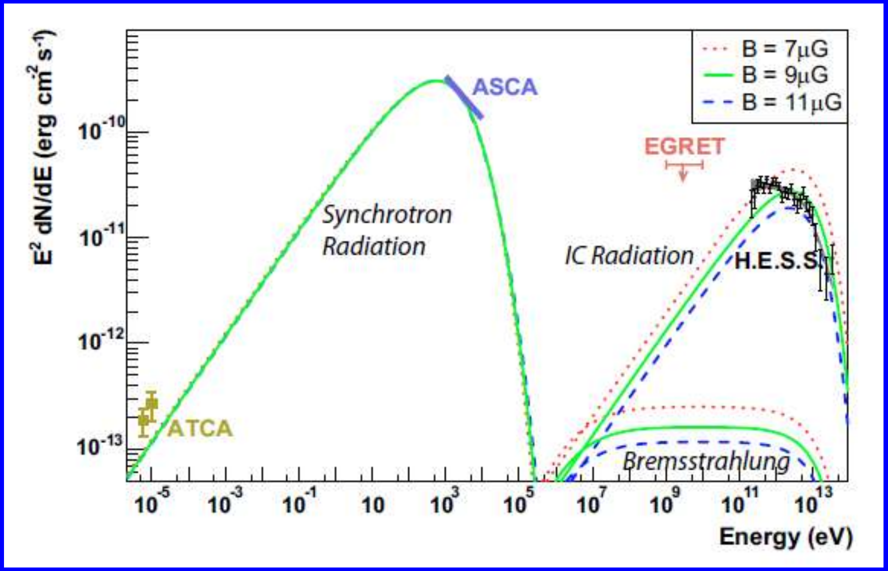
$$\pi^{\pm} \to \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu}) \to e^{\pm} + \nu_{e}(\bar{\nu}_{e}) + \nu_{\mu} + \bar{\nu}_{\mu}$$

C.f. $p + \gamma \to \Delta \to$ **P+π0 ; π0 → γ+γ**

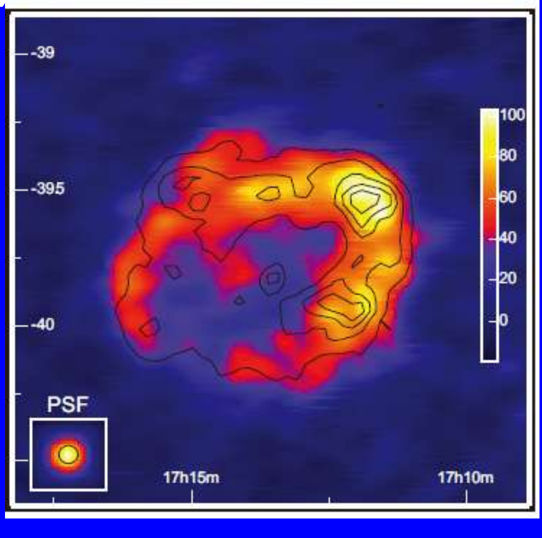
C.f. 2 IC: Gamma + e- → Gamma + e- : No neutrinos

Supenova Remnant 1713.7-3946





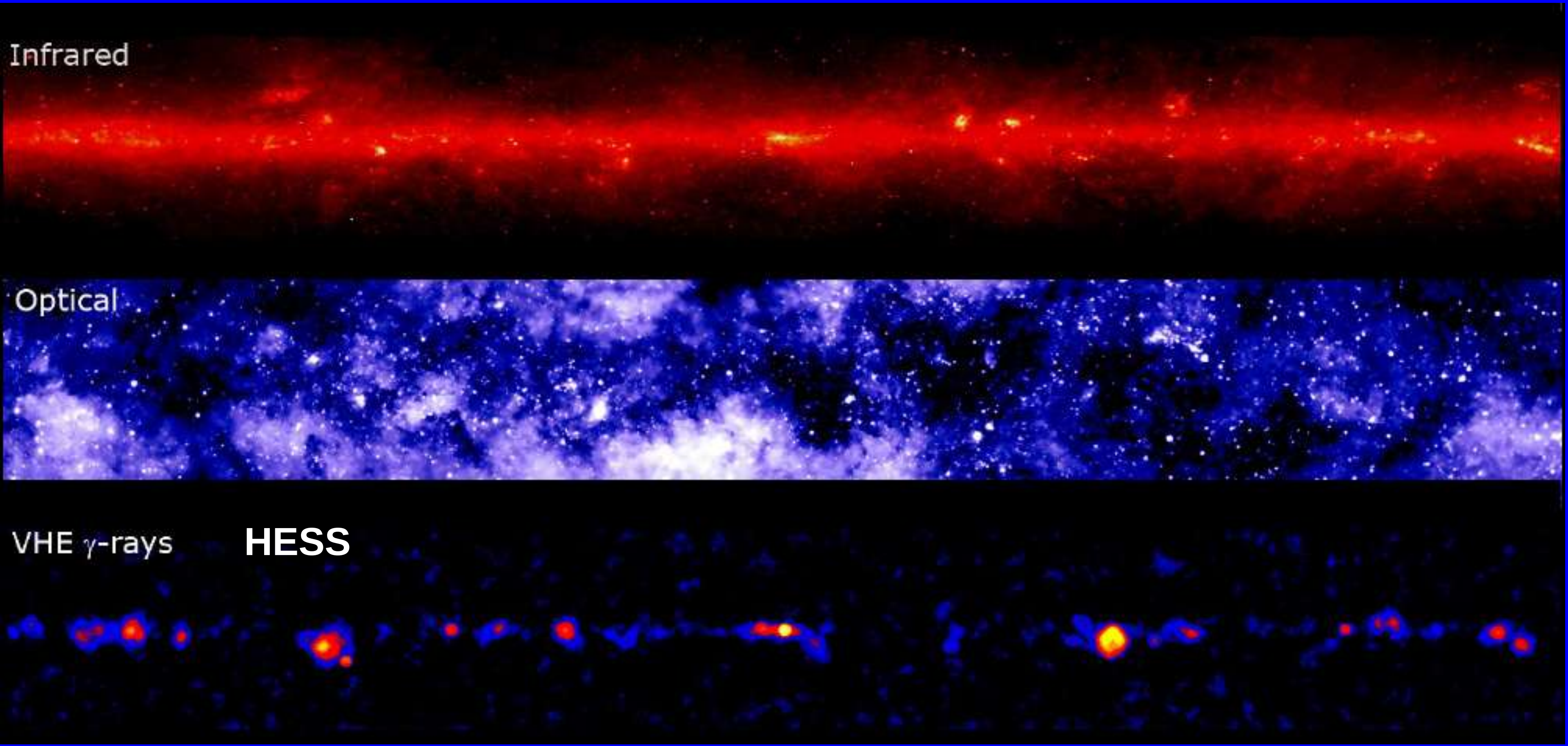
Left： Proton model (Pion productions by pp interactions)
Right：Electron model (Inverse Comptons by electrons)
Aharonian+05,06



In their papers, it is concluded that the proton model is favored. But very careful discussion is Necessary to derive this conclusion.

If VHE neutrinos are observed from this source, That can be strong evidence of proton acceleration.

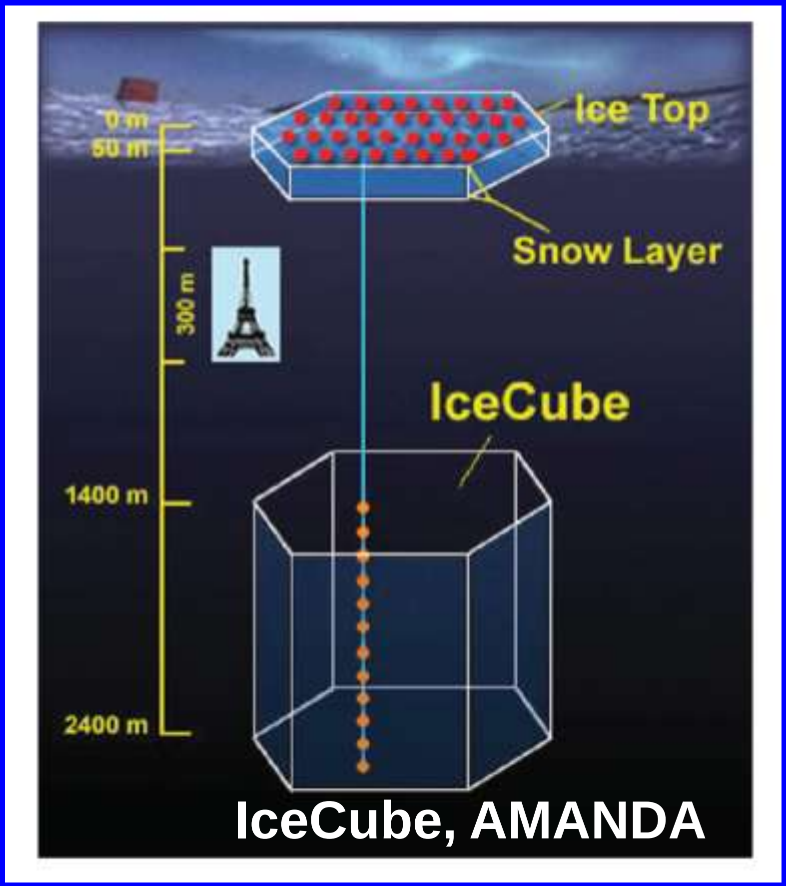
Anyway, new window should bring us a new picture of the universe!



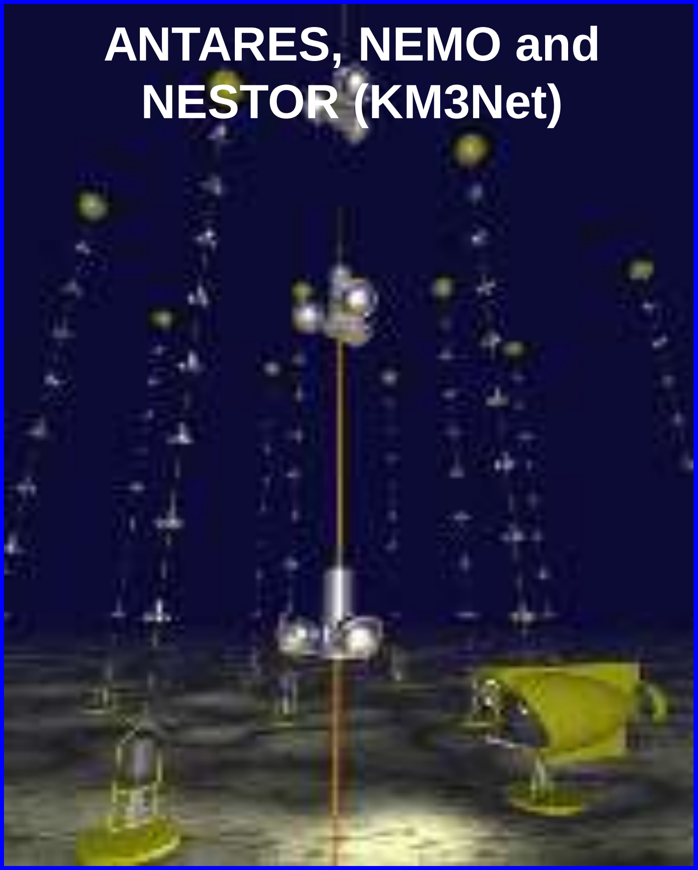
From **Arache Djannati-Ataï**

Difficulty of Detecting VHE Neutrinos

No evidence for a source of extraterrestrial neutrinos yet



IceCube, AMANDA


ANTARES, NEMO and NESTOR (KM3Net)

The smallness of cross sections makes neutrinos special and important that bring new information of the sources. At the same time, the smallness also makes detection of neutrinos difficult.

- Sources of VHE Neutrinos

Candidates for Sources of VHE Neutrinos

- Active Galactic Nuclei (AGN)
- Gamma Ray Bursts (GRBs)
- Supernova Remnants
- Starburst Galaxies
- Cluster of Galaxies
- Pulsars
- Objects from the early universe (strong constraints exists)

Various Candidates. Physics involved in is similar with each other.

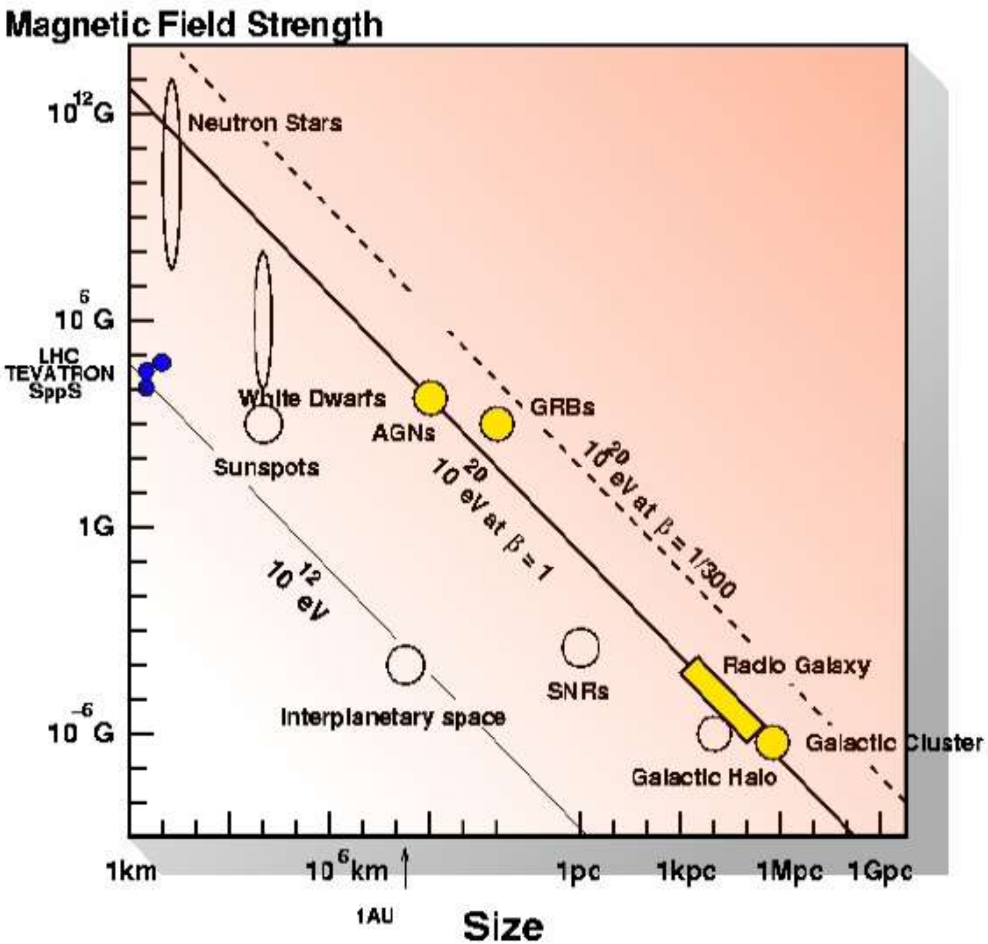
Acceleration mechanism：
Mainly Shock Acceleration Mechanism are Considered.
c.f. Acceleration due to Electric Potential.

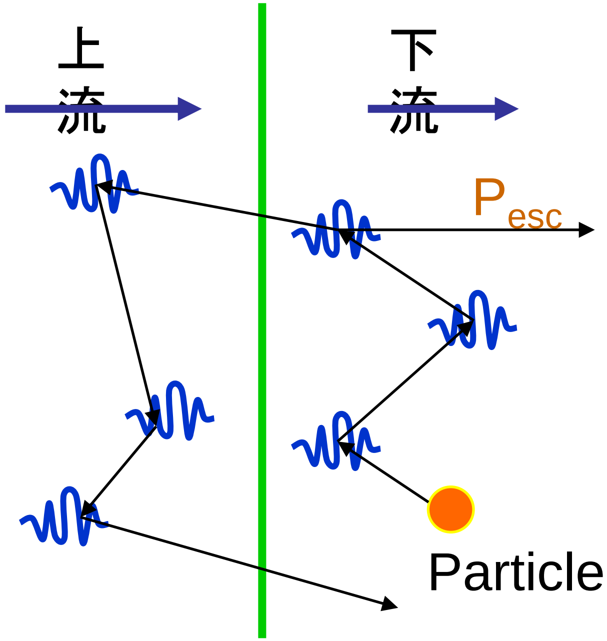
Emission mechanism：P-gamma or PP for protons.

Compositions：Proton and/or Nuclei

Particle Acceleration

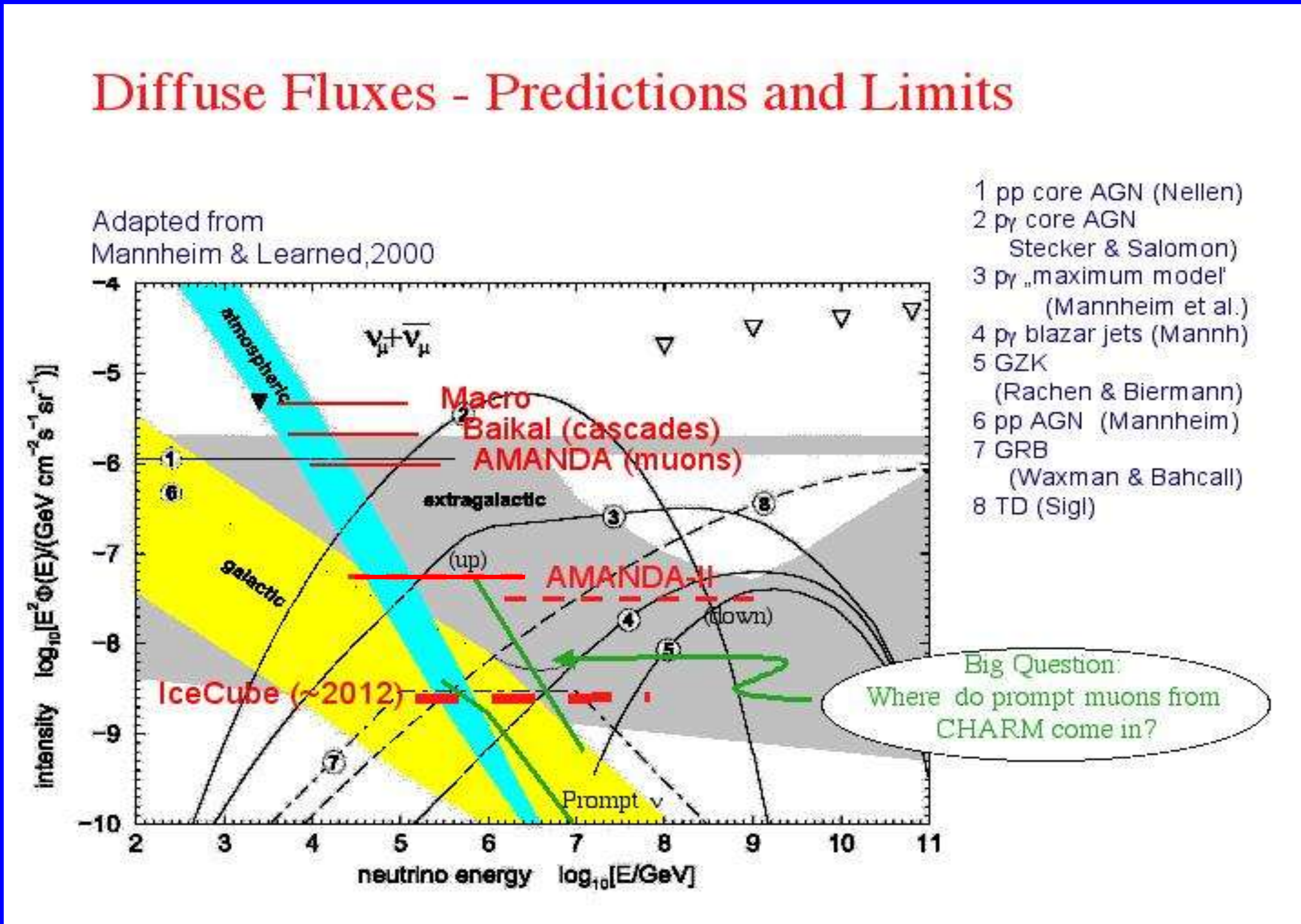
- Shock acceleration is frequently discussed.
- When we believe the Fermi acceleration (the shock acceleration is a kind of Fermi acceleration), the Larmor radius has to be smaller than the system size of the accelerator.





The Shock Acceleration

Expected Diffuse Neutrinos from Various Candidates



Source Candidate 1: AGN (1)

Neutrinos from Core: ex. Stecker and Salamon 96; Muniz and Meszaros 04
Neutrinos from Jets: ex. Mucke, Protheroe, Engel, Rachen, Stanev 03; Mannheim, Protheroe, Rachen 00; Becker, Biermann, Rhode 05

Source Candidate 1: AGN (2)

Figure from Sikora et al. 94

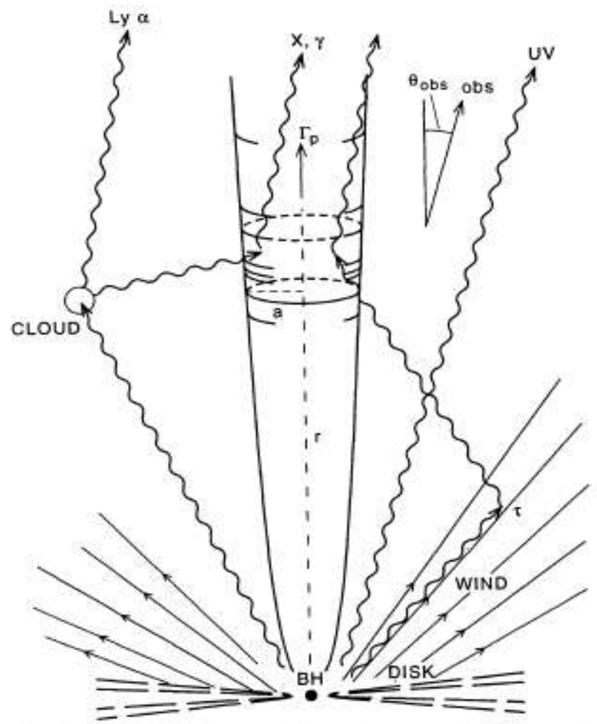
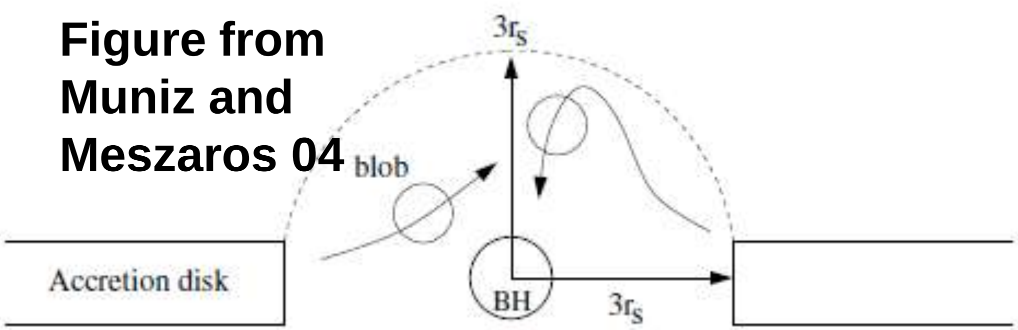


FIG. 2.—Geometry of the source. The radiating region, denoted by short cylinder of dimension a, moves along the jet with pattern Lorentz factor Γ_p. Underlying flow moves with Lorentz factor Γ, which may be different.

AGN Jet models:
Shocks in the Jet

Optically thin models.
Observational constraint comes from
Diffuse GeV gamma-rays.

Figure from Muniz and Meszaros 04

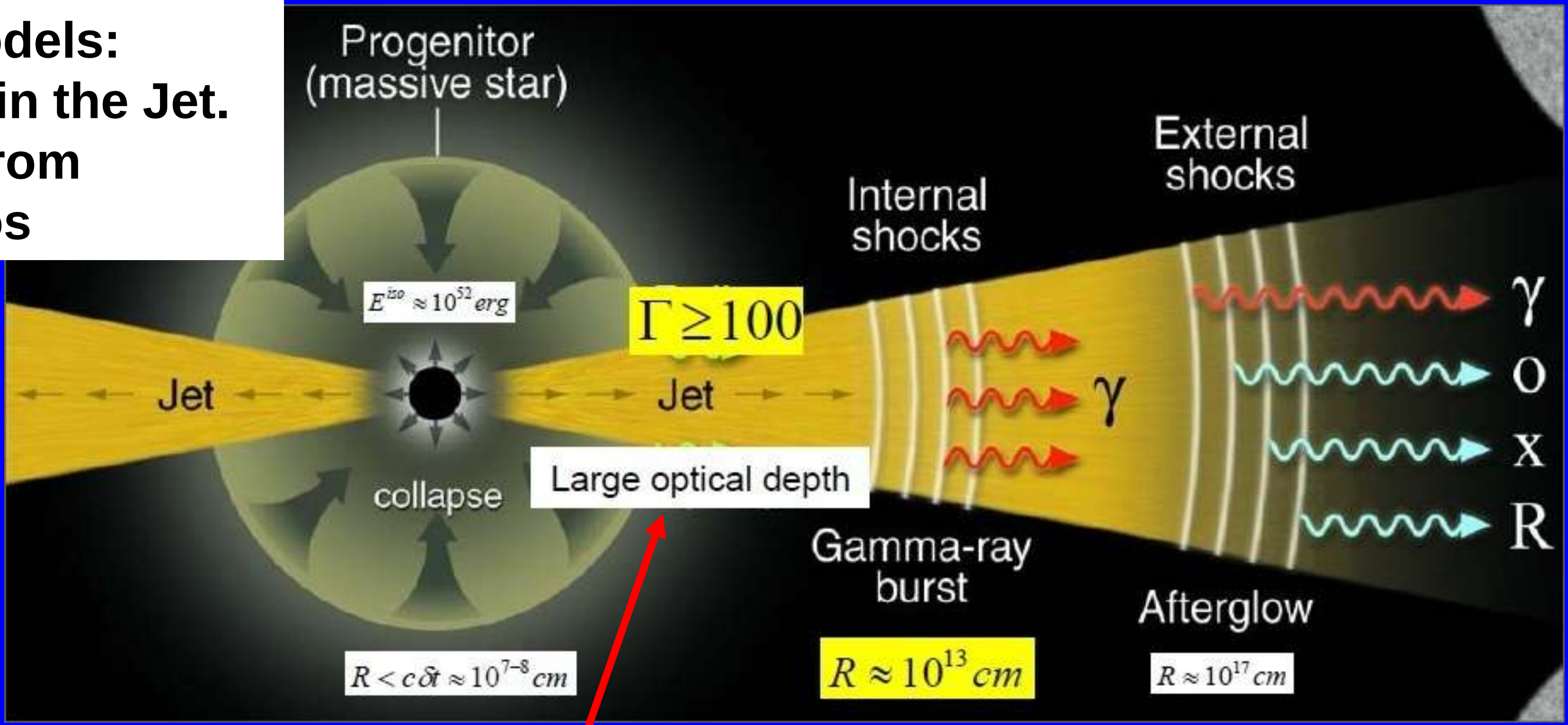


AGN core models:
Shock or
Collision of Blobs

Optically thick models.
observational constraints come (came?)
From diffuse X-rays.
Now stronger constraints have
Been drawn by neutrinos!

Source Candidate 2: (Long) GRB

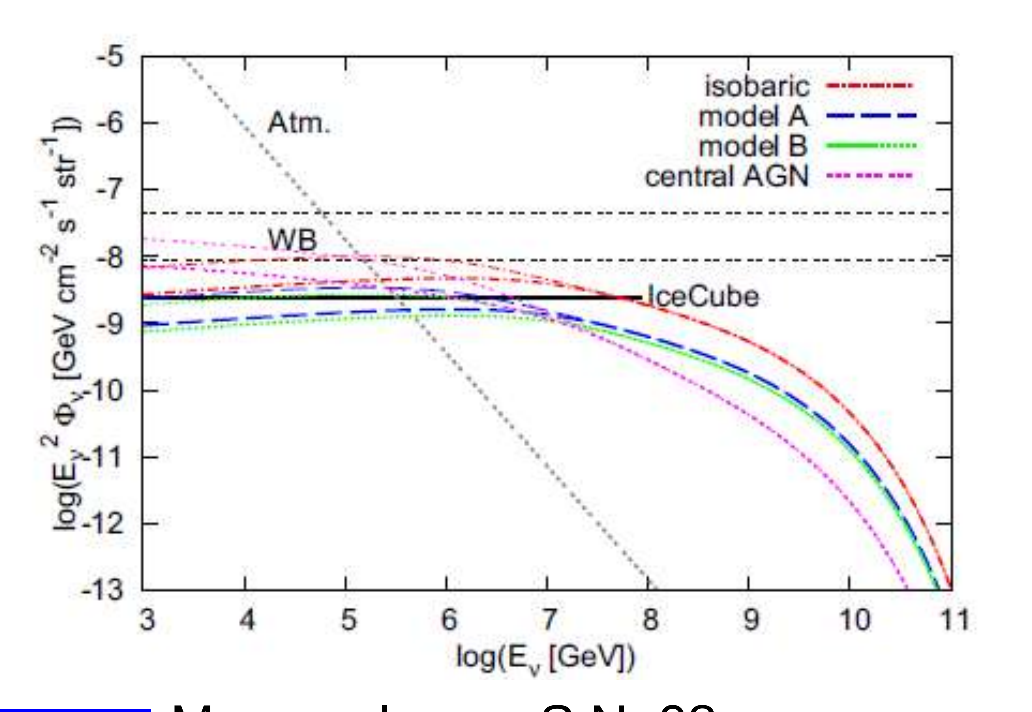
GRB models:
Shocks in the Jet.
Figure from
Meszaros



Optically thick models.
Ex. Corked Jet inside a progenitor.
Basically, no constraint is derived from the observations
(It can be bright only in neutrinos).

Optically thin models.
Observational constraint comes from Ultra-High Energy Cosmic Rays (UHECRs).
Waxman and Bahcall (WB) limit.

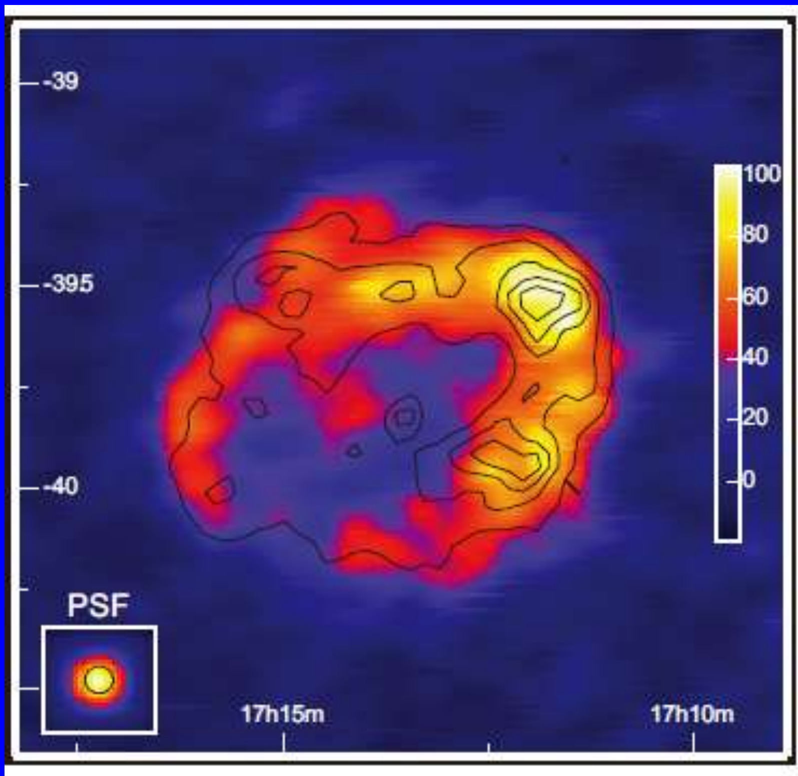
Source Candidate 3: Cluster of Galaxies



Murase, Inoue, S.N. 08
See also Marco, Hansen, Stanev 06

- Shocks are driven by accretion of gas as well as galaxies onto a cluster of galaxies.
- Neutrinos can be produced by PP and/or Pγ interactions.
- At present, no strict observational constraint is derived, although CGs are optically thin objects.

Source Candidate 4: Supernova Remnants



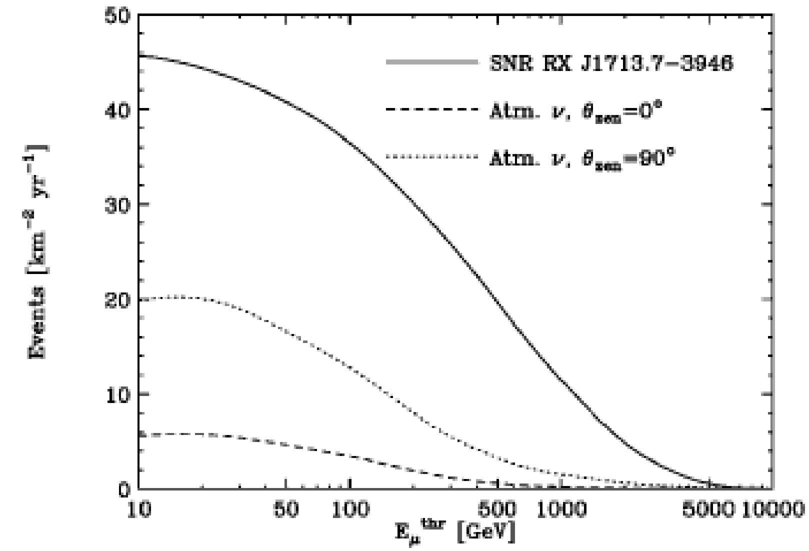


FIG. 1.—Neutrino event rate per year from RX J1713.7−3946 as a function of the muon energy threshold in a kilometer-scale neutrino telescope. Also shown is the event rate expected in a 1° × 1° bin in the sky from atmospheric neutrinos. The dashed curve shows the prediction for vertical downgoing atmospheric neutrinos, and the dotted the corresponding one for horizontal atmospheric neutrinos.

Image of RX J1713.7-3946
Color: HESS
Contour: ASCA (1- 3keV)
Aharonian+06
PP interactions, optically thin.

Expected neutrino events from RX 1713.7-3946 (Muniz and Halzen02). Note that this calculation is based on the observations of CANGAROO (02)

§ Method of Estimation of VHE neutrinos: Case of GRBs

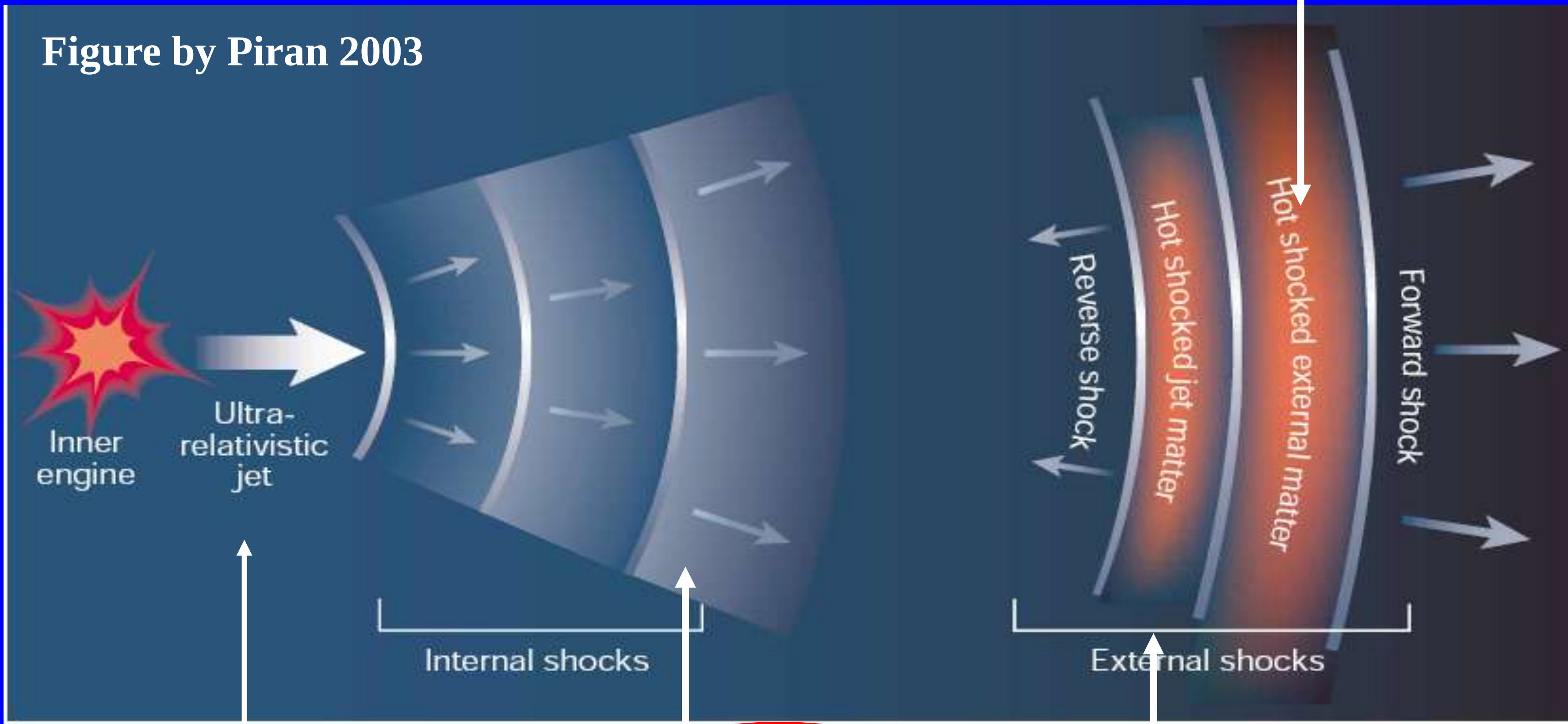
Similar to other possible sources such as AGNs, Starburst Galaxies, Cluster of Galaxies, and so on.

Ex. Waxman and Bahcall 97; Waxman and Bahcall 01; Dai and Lu 01; Dermer 02; Razzaque and Meszaros 03; Zhang et al.03; Fan, Zhang, and Wei 05; Murase and S.N. 06a; Murase and S.N. 06b; Murase, Ioka, S.N.,Nakamura 06; Gupta and Zhang 07; Murase 07,08; Iocco, Murase, S.N., Serpico 08; Murase, Meszaros, Zhang 09; Wang and Dai 09.

Where are very high-energy neutrinos produced?

10^13 – 10^15 cm

Dermer 02 TeV-PeV Neutrinos
Dai and Lu 01



Bahcall and Meszaros 00
Razzaque and Meszaros 03
Zhang et al. 03
Iocco,Murase,S.N.,Serpico 08
GeV-TeV Neutrinos

Waxman and Bahcall 97
Murase and S.N. 06a,b
Gupta and Zhang 07
Wang and Dai 09
TeV-PeV Neutrinos

Waxman and Bahcall 01
TeV-EeV Neutrinos

Procedure to Estimate Flux of Neutrinos

- Properties of Soft Photons

  Energy density, Spectrum

- Efficiency of Fermi Acceleration

  Maximum energy, Amount of non-thermal protons

- Calculation of pγ Interections

  Neutrino spectrum from a GRB is obtained

- GRB rate history in the Universe

  Diffuse Neutrino Background is obtained

Properties of Soft Photons: Energy density, Spectrum

In this model, soft photons are gamma-rays of GRBs!

Usually, the spectrum of a GRB has a break (Band et al. 93).

Observed isotropic energy is $E^{iso}_{\gamma,tot} = f_b^{-1} E_{\gamma,tot} \sim (10^{52} - 10^{54})\,\mathrm{ergs}$

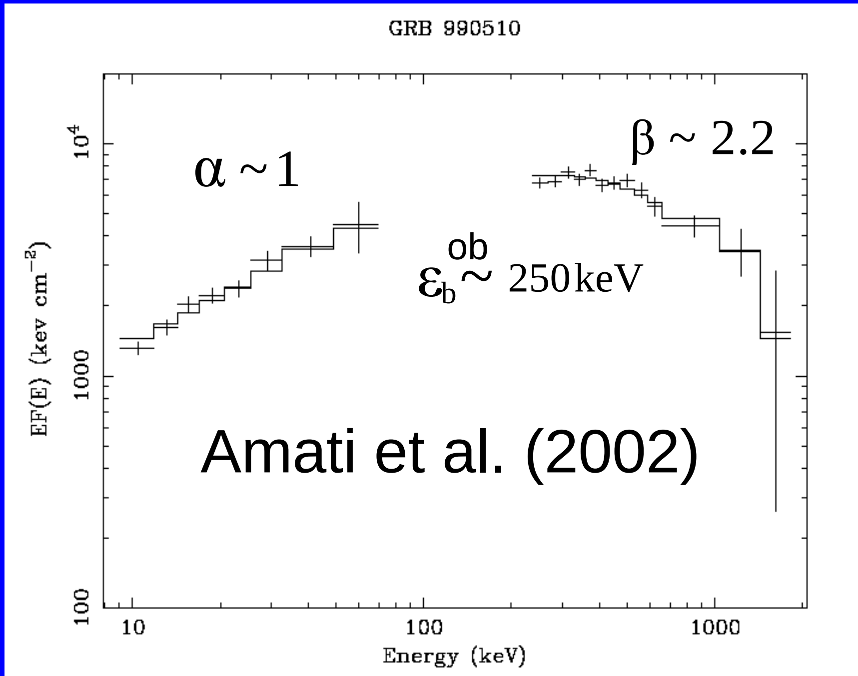
Energy density of gamma-rays (it is X-rays in the fluid rest frame) in the fluid rest frame depends on the $E^{iso}_{\gamma,tot}$ and location of the internal shocks.

$$U_\gamma \sim \frac{E^{iso}_{\gamma,tot}}{\Gamma r^3}$$

: Energy density of Gamma-rays in the Fluid-rest frame

r : Location of the internal shocks (1E+13-1E+15)cm

(Observed (beaming effect is taken into account) energy is $E_{\gamma,tot}$=1.24E+51 erg)



Efficiency of Fermi Acceleration:
Maximum energy, Amount of non-thermal protons

$t_a = t_a(E,B)$: accerelation timescale $$t_a = f R_L / c\beta^2$$

f is (1-10) (Kulsrud, 79). β is the Alfven velocity. $\beta \sim 1$

t_d: dynamical timescale $$t_d \sim r_d / \gamma c$$

r_d is the distance from the center to the acceleration regions.
γ is the bulk lorentz factor

$t_{sy} = t_{sy}(E,B)$: synchrotron loss timescale $$t_{sy} = (6\pi m_p^4 c^3 / \sigma_T m_e^2) E^{-1} B^{-2}$$

$t_{p\gamma}$: Cooling timescale due to $p\gamma$ interactions $$p + \gamma \rightarrow \Delta \rightarrow n + \pi^+ \quad \kappa_p \sim 0.2$$

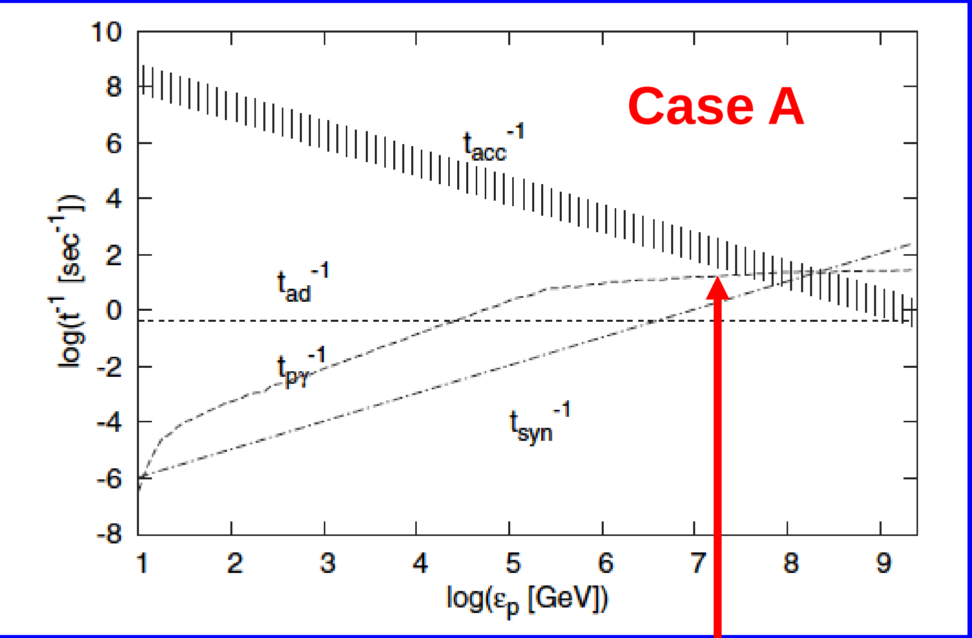
Calculated by Geant4

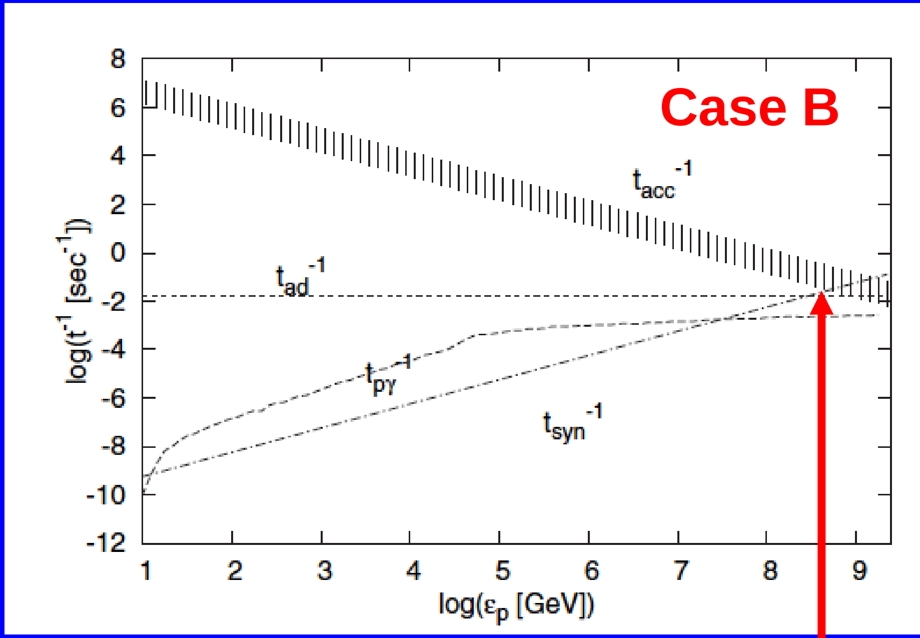
$t_a < \min(t_d, t_{sy}, t_{p\gamma})$ **Protons are accelerated when this condition is satisfied.**

$t_{p\gamma} < t_d$ **All accelerated protons interact with photons without escaping From the GRB (in this case, no CRs (including UHECRs) are ejected)**

The fraction of energy lost by photo-pion productions is $f_\pi = \min(1, t_d/t_{p\gamma})$.

How is E_{max} determined?
How much are protons accelerated?





Case A: r=2E+13cm, $E_\gamma^{iso} = 2 \times 10^{51}$ ergs
Photon density is high and
Cooling timescale due to photopion
Production determines Emax.
Emax is relatively low.

Case B: r=5E+14cm, $E_\gamma^{iso} = 2 \times 10^{52}$ ergs
Photon density is low, so Emax
Is determined not by photopion
Production but by synchrotron cooling.
Emax is relatively high.

How much protons are accelerated? Nobody knows.

→ **Parameter survey.**

$$U_p = \varepsilon_{acc} U_\gamma \approx \varepsilon_{acc} U_e$$

Cf. Waxman & Bahcall 97

Calculation of pγ Interections

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

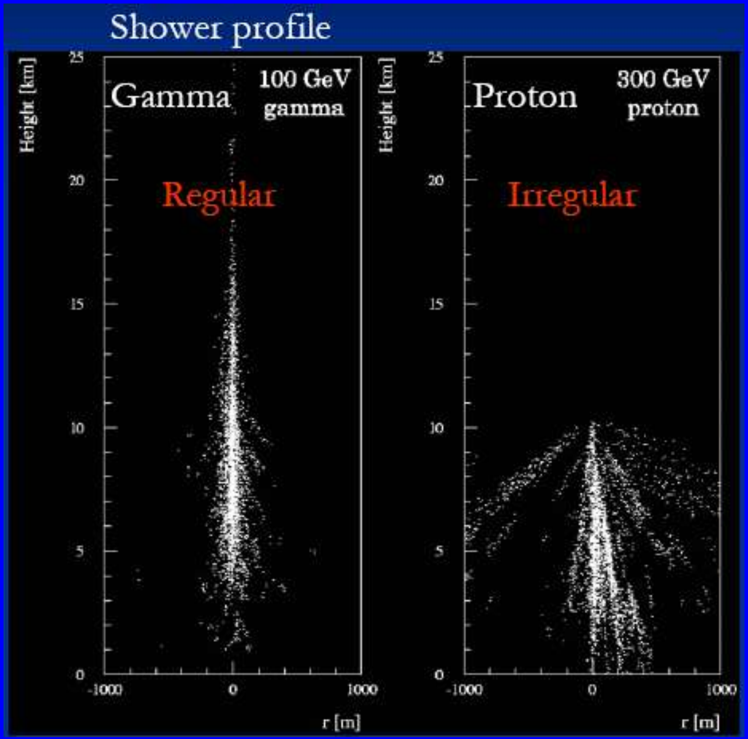
Multi-pion productions $p + \gamma \rightarrow N\pi^{\pm} + X \quad \kappa_p \sim (0.5\text{—}0.7)$

Geant4
Multiplicity + Inelasticity

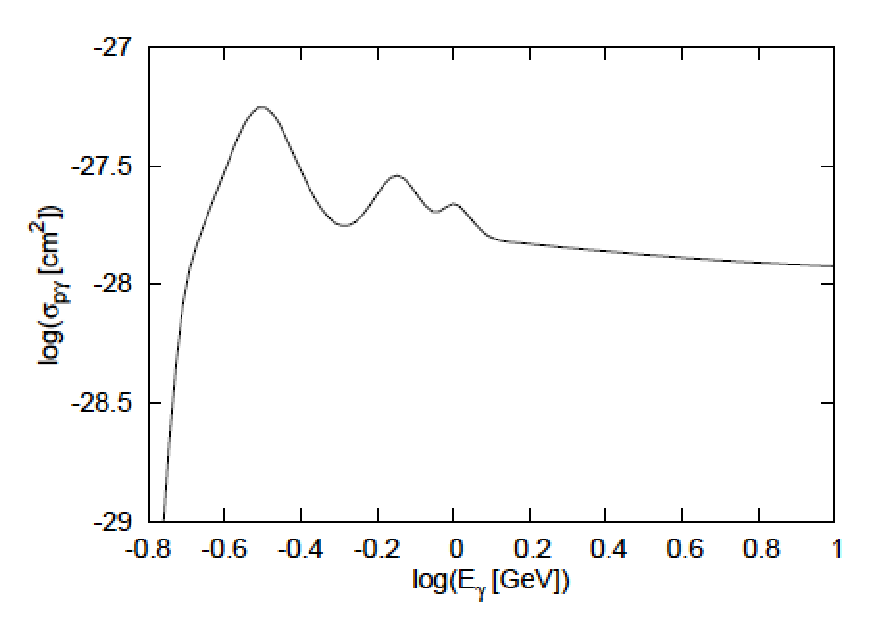
$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu}) \rightarrow e^{\pm} + \nu_e(\bar{\nu}_e) + \nu_{\mu} + \bar{\nu}_{\mu}$$

Cooling Processes
- **Synchrotron Loss**
- **Adiabatic Loss**

Energy spectrum of muon-type Neutrinos from a GRB is obtained.



Examples of calculated Shower profile by Geant4 Mori (2004).



Inclusive cross section of photomeson production

GRB rate history in the Universe

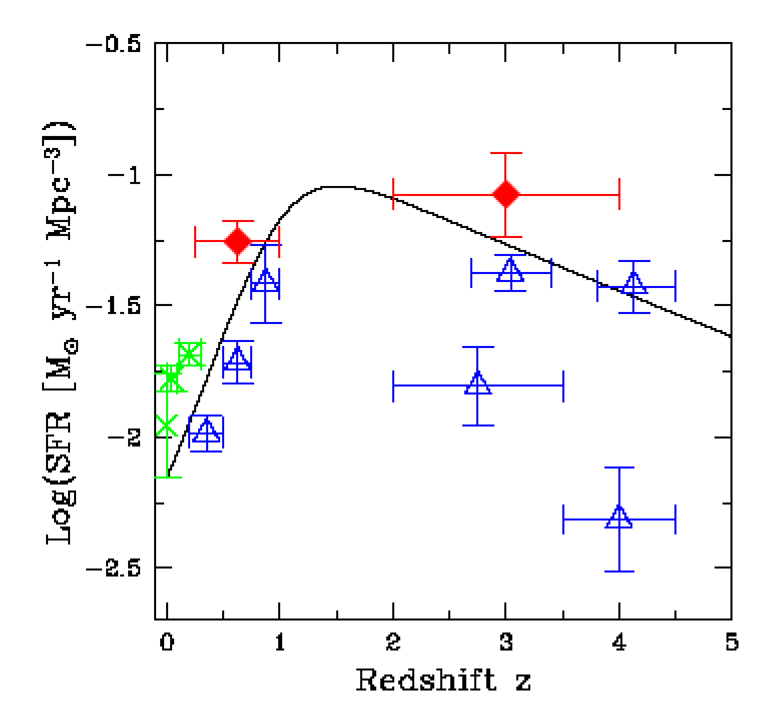
GRB Diffuse Neutrino Background is obtained using the GRB rate history in the Universe.

$$\frac{dF_\nu}{dE_\nu d\Omega} = \frac{c}{4\pi H_0}\int_{z_{\min}}^{z_{\max}} dz R_{\rm GRB}(z)\frac{dN_\nu((1+z)E_\nu)}{dE'_\nu}\frac{1}{\sqrt{(1+\Omega_m z)(1+z)^2 - \Omega_\Lambda(2z+z^2)}},$$

$z_{\min} = 0$, and $z_{\max} = 7$ or $z_{\max} = 20.$

(neutrinos/GeV/cm^2/s/sr)

Assumption: GRB rate $\propto$ star formation rate (Totani (1997))



Ando and Sato (2004)

GRB rate = SFR × $f_{cl} \times \frac{\int_{35}^{125} dm\,\phi(m)}{\int_{0.4}^{125} dm\,m\,\phi(m)}$

Fitting formula:
Porciani and Madau (2001)

IMF $(\phi(m) \propto m^{-2.35})$

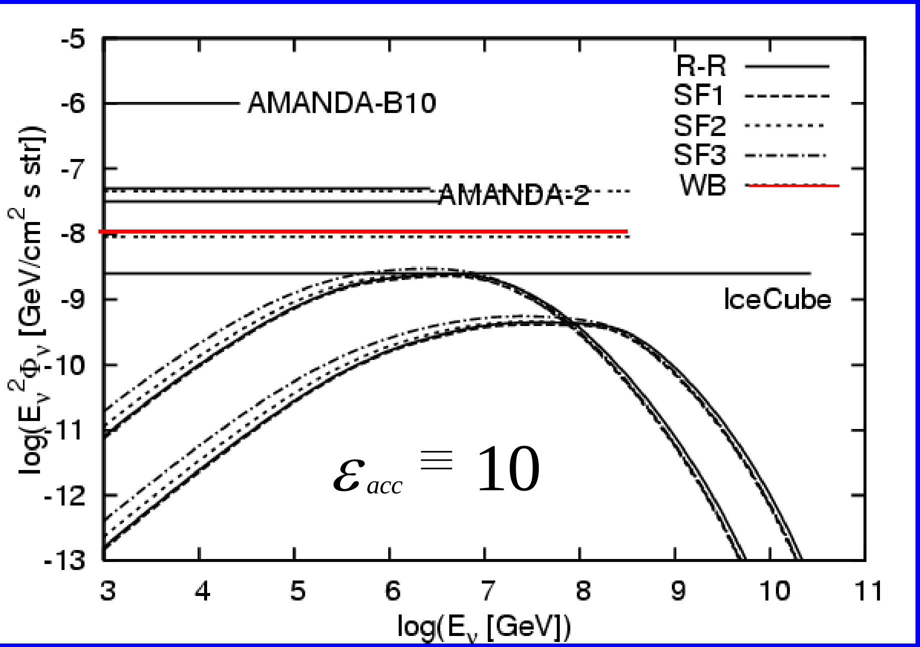
Normalization factor, fcl, is the possibility That a massive star causes a GRB, and Determined by the present GRB rate.

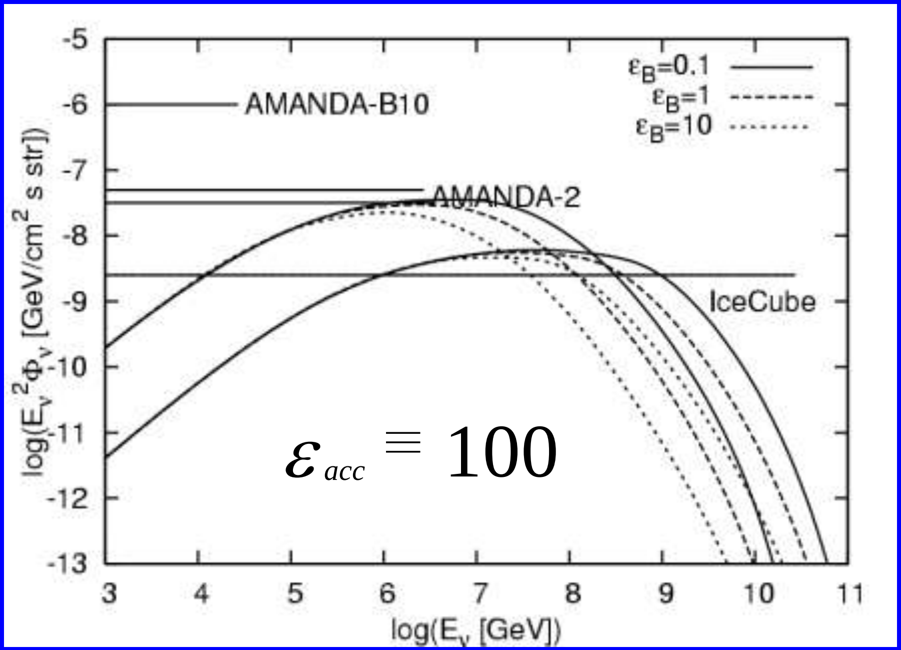
$R_{\rm GRB}(0) = 17 h_{70}^3\ \mathrm{yr}^{-1}\ \mathrm{Gpc}^{-3}$ Shumidt (2001)

→ **fcl ~1.6E-3**

GRB Diffuse Neutrino Background

Murase & S.N., PRD, 063002 (2006)





Upper lines: Case A, Lower lines: Case B

Case A: Flux is higher, but energy is lower, CRs are not ejected from GRBs

Case B: Flux is lower, but energy is higher, CRs(UHECRs) are ejected from GRBs.

Event rates@km^2 detector:

$\varepsilon_{acc} = 10$ **Case A: 17 events per yr, Case B: 1.5 events per yr.**

$\varepsilon_{acc} = 100$ **Case A: 170 events per yr, Case B: 15 events per yr.**

Promising!

Making Constraints from Observations (1)

Brief derivation of Waxman & Bahcall limit

Procedures:

(i) UHECRs are assumed to come from GRBs.

(ii) Required Injection Rate of UHECRs: B*E^-2 [particles/eV/Mpc^3/yr].

(iii) Production Rate of Cosmic Rays by GRBs:

A*E^-2 [particles/eV/Mpc^3/yr].

(iv) The fraction of energy lost by photo-pion productions is

f_π= min(1, td/tpγ). Optically thin is assumed.

→ **UHECRs from GRBs = A*(1-f_π)*E^-2 = B*E^-2**

Neutrinos from GRBs = A*f_π*(E/0.05)^-2

As long as f_π <<1, A ~ B

→ **Neutrinos from GRBs = B*f_π*(E/0.05)^-2< B*(E/0.05)^-2**

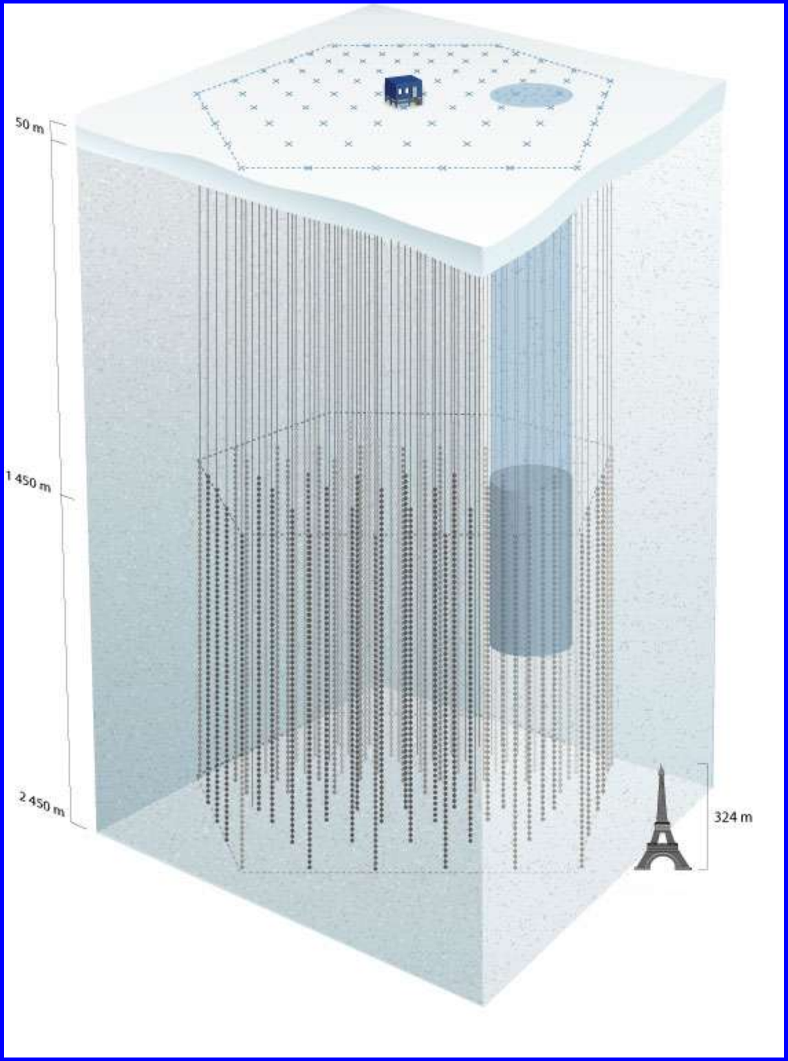
Waxman and Bahcall limit

Making Constraints from Observations (2)

- In the case of GRBs, UHECRs are frequently used as a tool to constrain the flux of VHE neutrinos.
- On the other hand, in the case of AGNs, X-rays and/or GeV gamma-rays background have been frequently used.
- Since the constraint by UHECRs is severer than that by X-rays/GeV-gamma, resulting flux of VHE of neutrinos from GRBs are smaller than that from AGNs.
- If UHECRs are used to constrain the flux of VHE neutrinos from AGNs, the resulting VHE neutrinos can be lower than W & B limit like GRBs (Mannheim, Protheroe, Rachen 2000).

§ Current Status of Observations of AMANDA/IceCube

AMANDA/IceCube



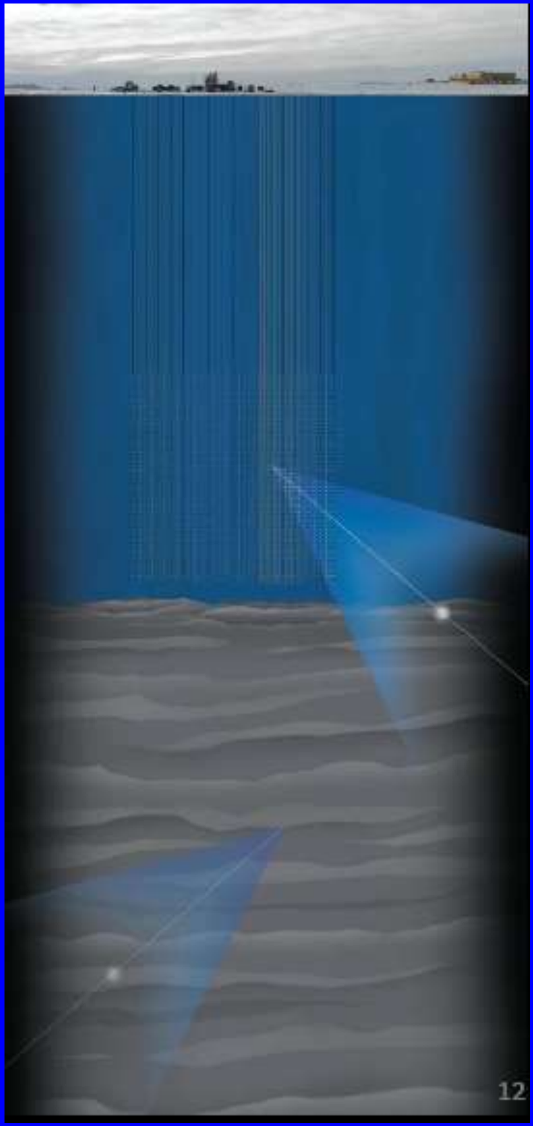
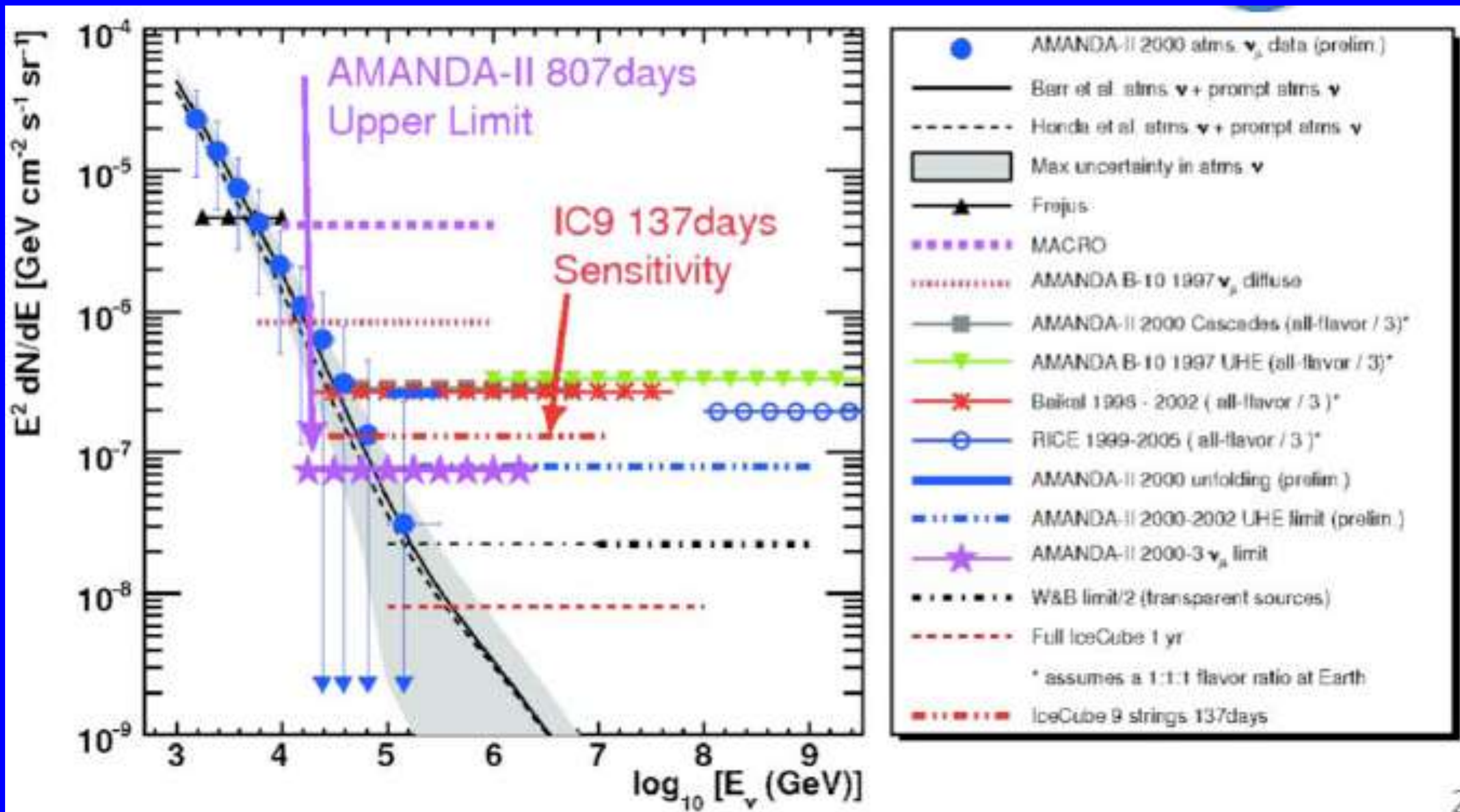


Figure from Dr. Georges Kohnen's talk at Moriondi (2009)

Constraints on the Energy Flux of VHE Neutrinos

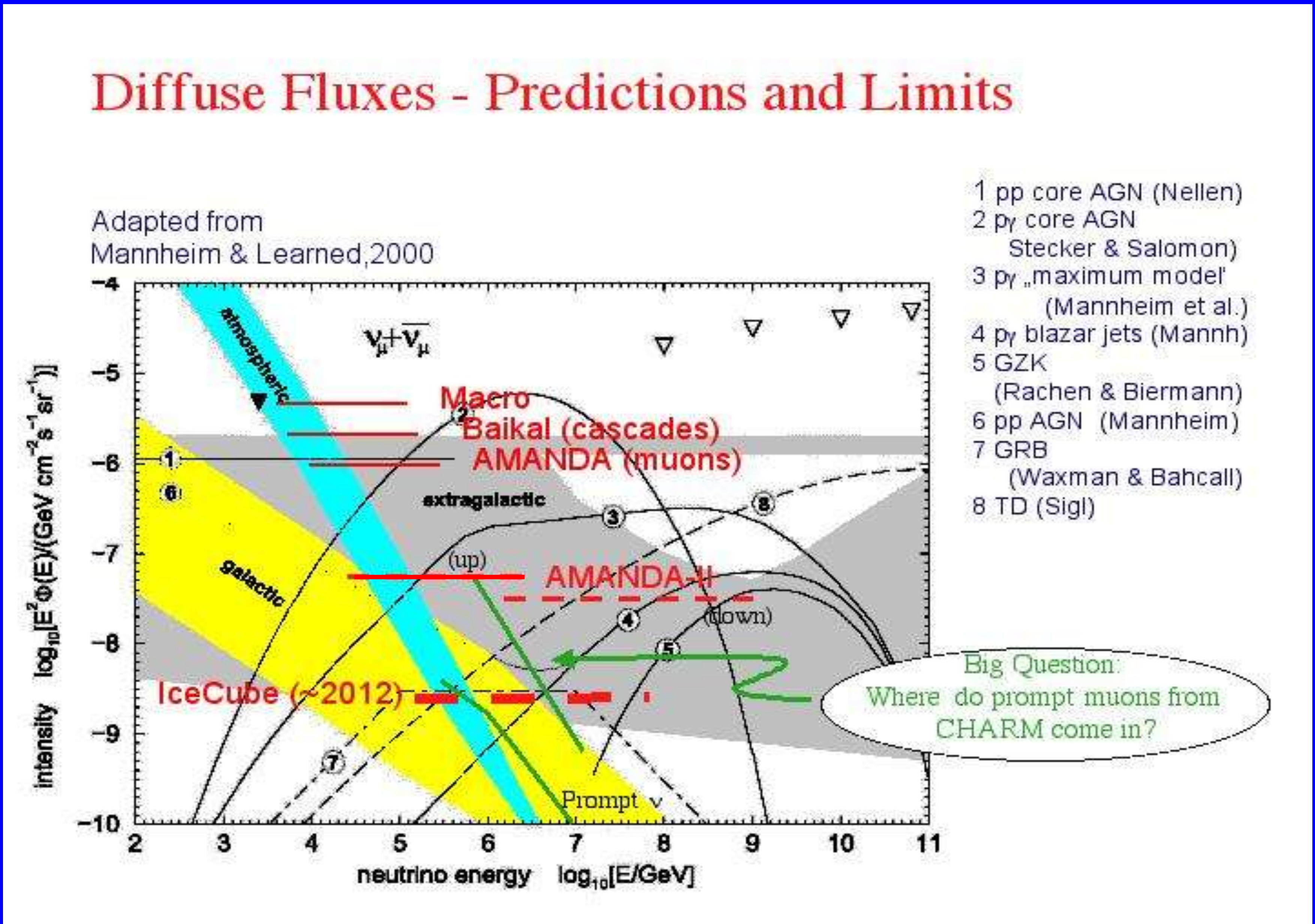
From Georges Kohnen's talk at Moriondi (2009)



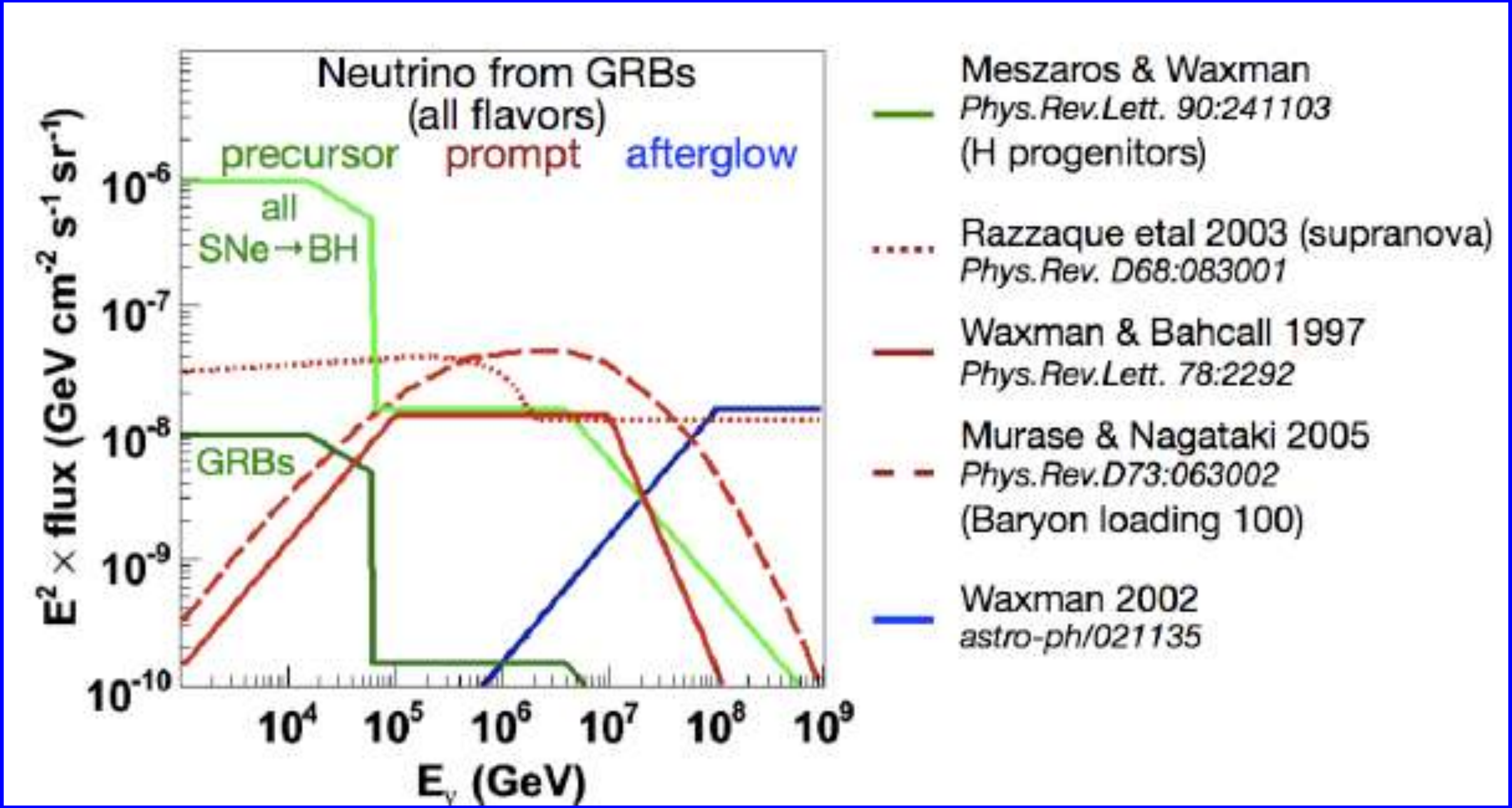
The upper limits on the ν_μ flux from sources with a $\Phi \propto E^{-2}$ energy spectrum

Some theoretical estimations are ruled out already.

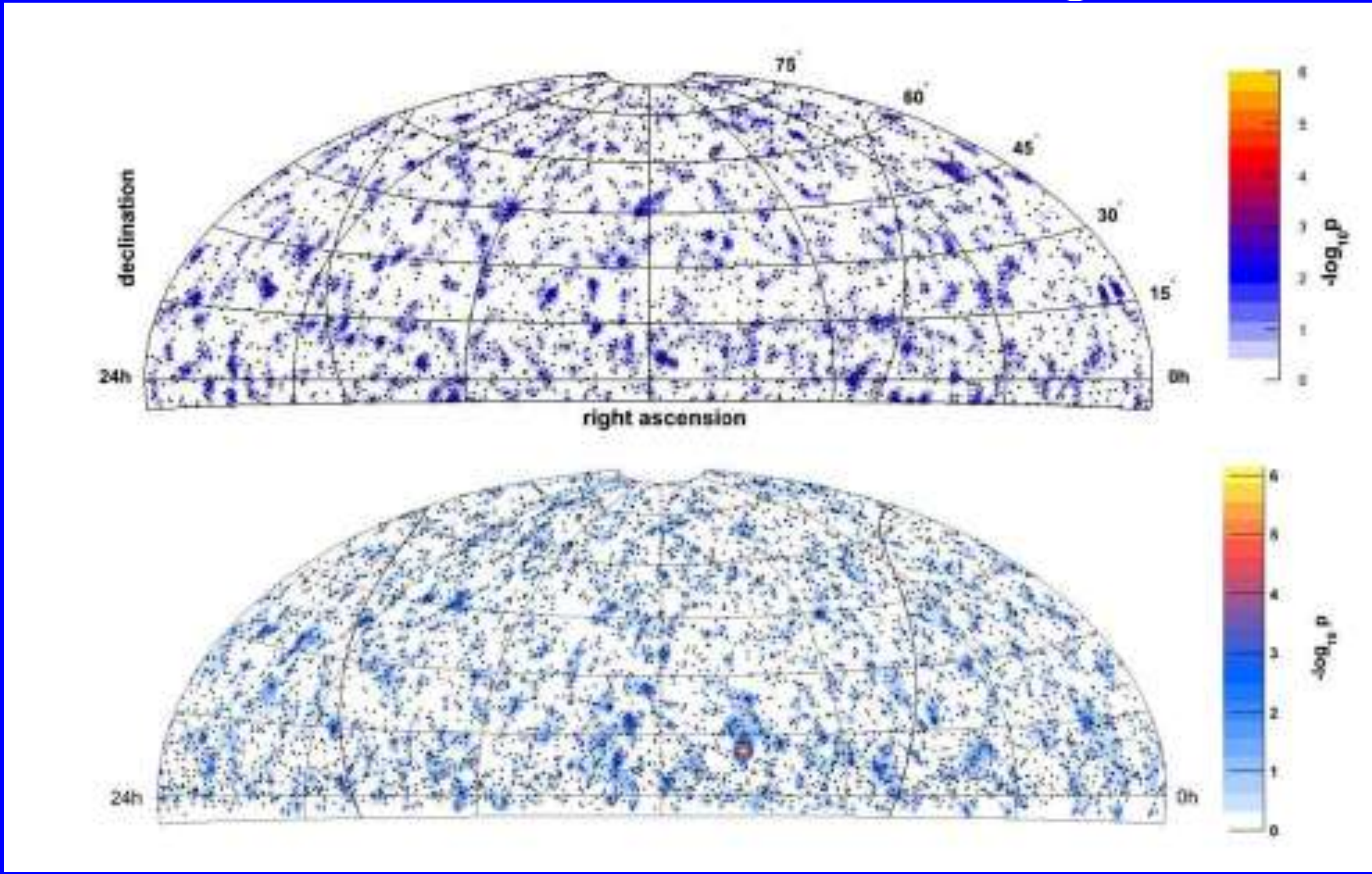
Expected Diffuse Neutrinos from Various Candidates



GRB neutrino flux predictions: templates for IceCube analysis



Arrival Directions of VHE Neutrinos Deviation from the Background



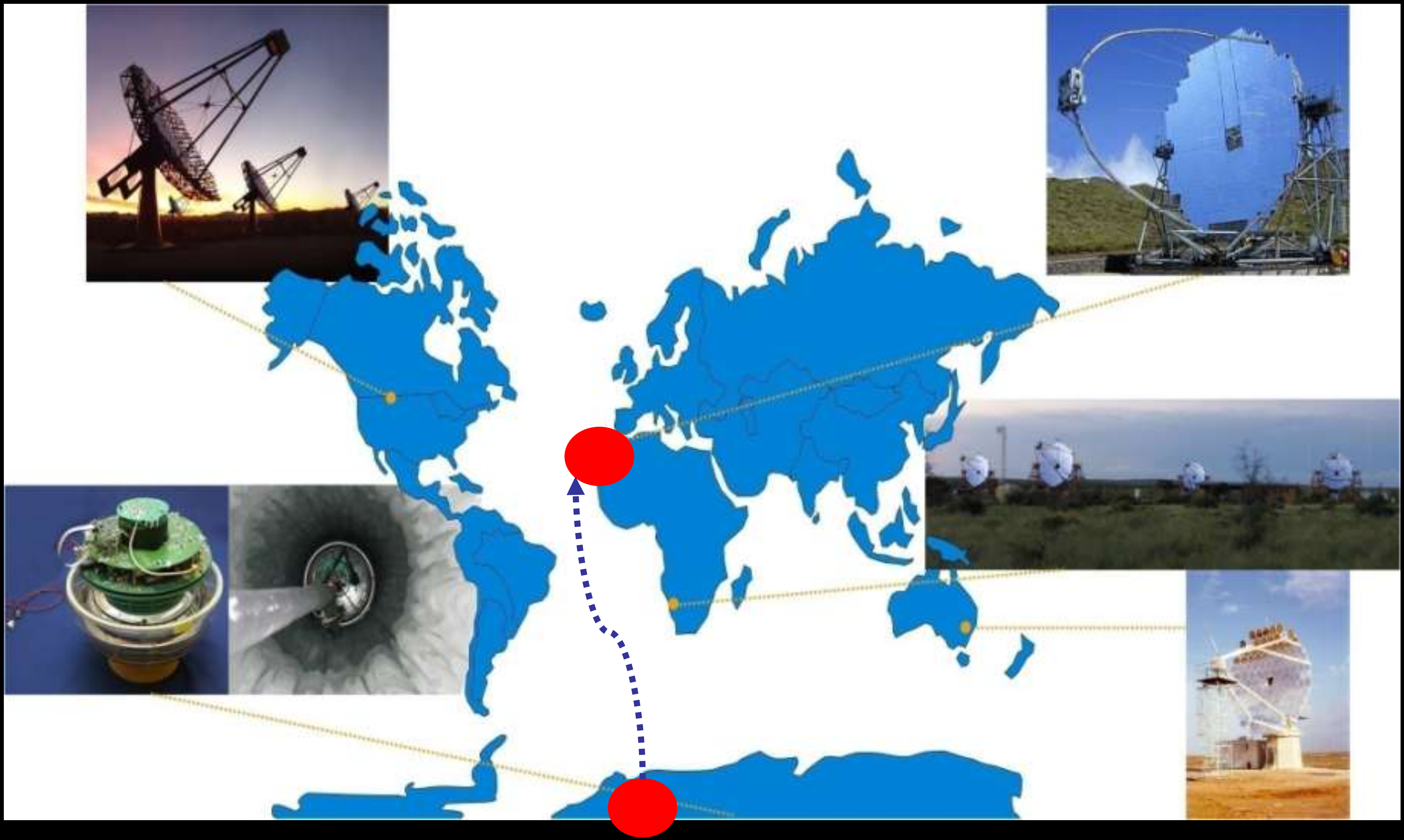
Alba for the IceCube Collaboration.(2009) Top:binned, Bottom: unbinned.

§ New Astronomy driven by VHE Neutrino Detection

Resconi プレゼンファイルより

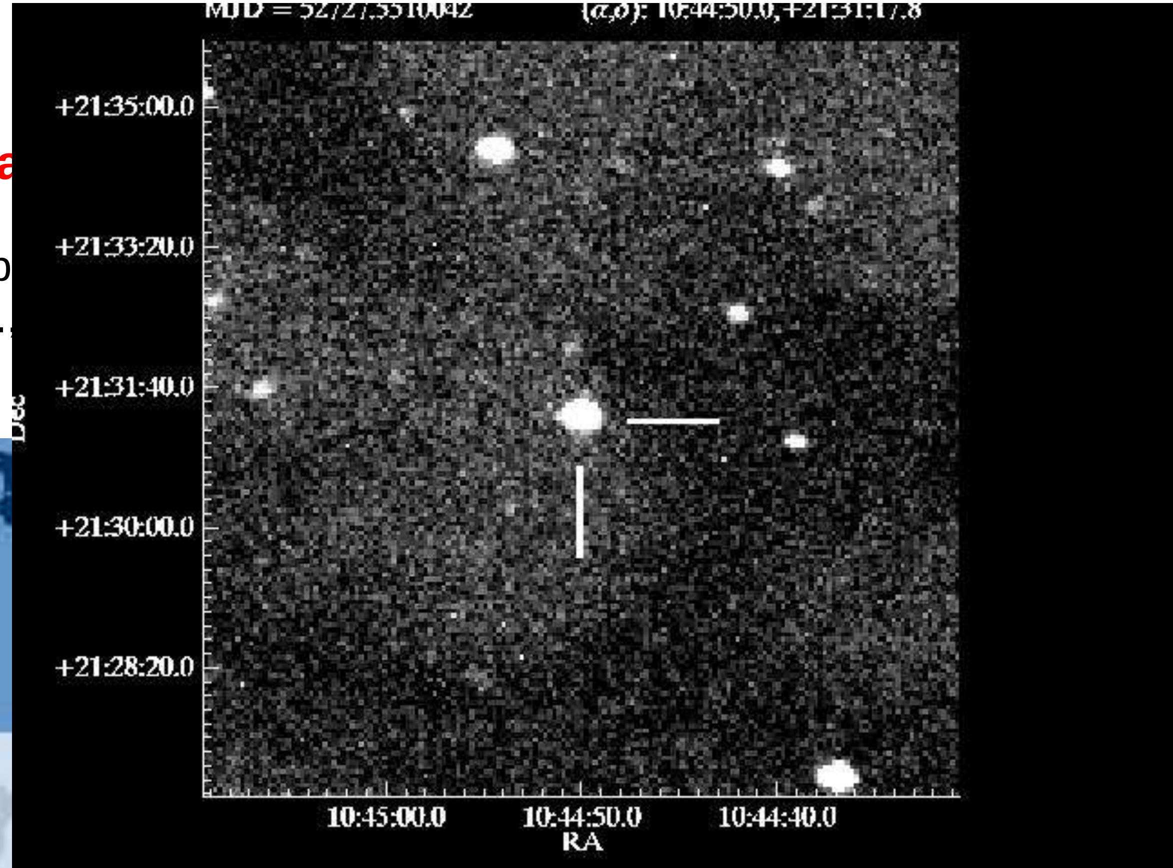
AMANDA – MAGIC
Alerts sent
Reaction within one day

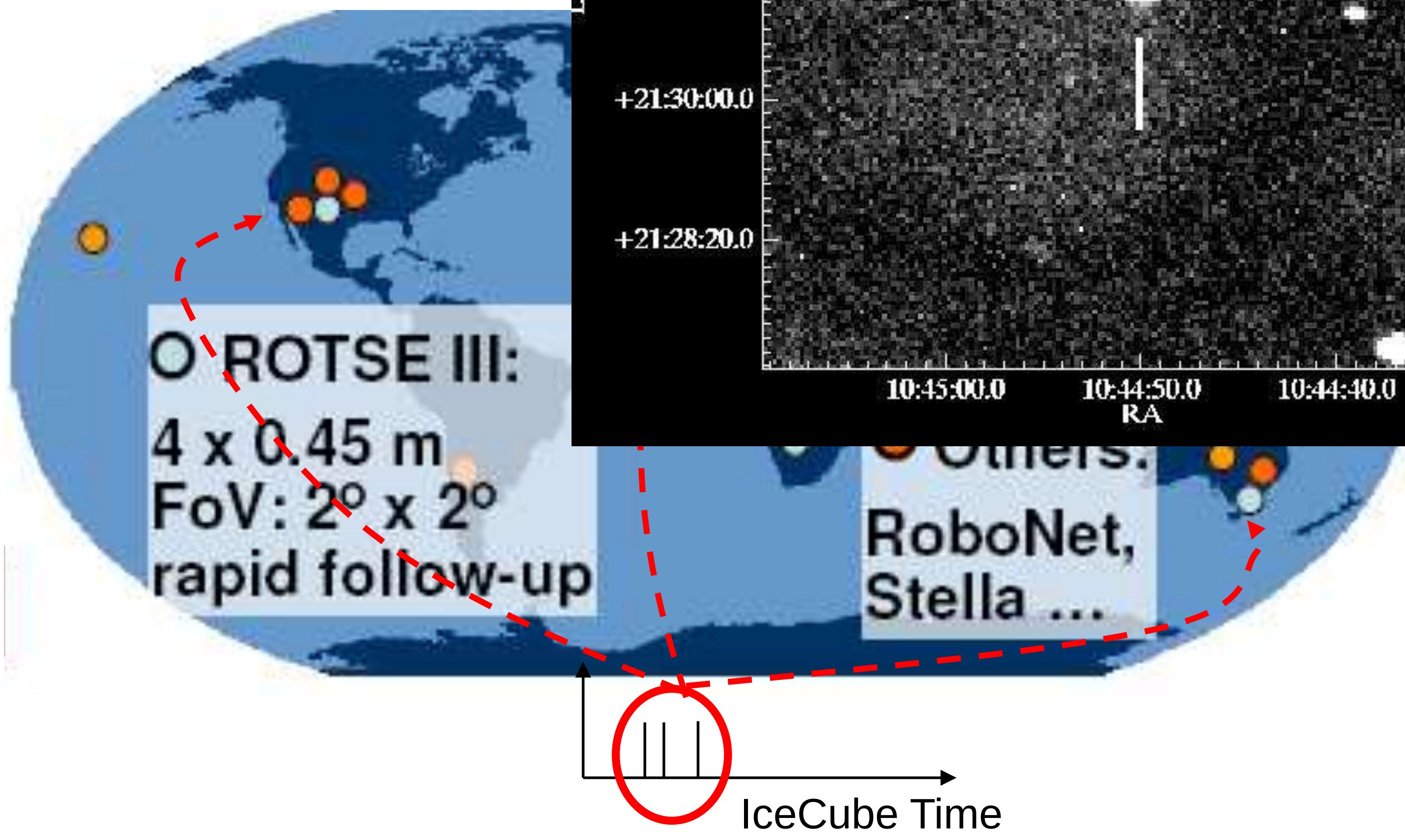
27th September to 27th November 2006
(E. Bernardini et al., astro-ph/0509396)



IceCube – ROTSE, optica

M. Kowalski, A. Mohr, astro-p
See also Murase, Ioka, S.N..





Elisa Resconi

- Summary

Summary

- Neutrinos come straightly from their sources even if they are far away from the Earth.
- Neutrinos bring information of the sources even if they are optically thick.
- Very High Energy neutrinos can be evidence of hadron accelerations.
- Neutrinos have a powerful potential to bring us a new window of the universe!