“第24回「宇宙ニュートリノ」研究会”

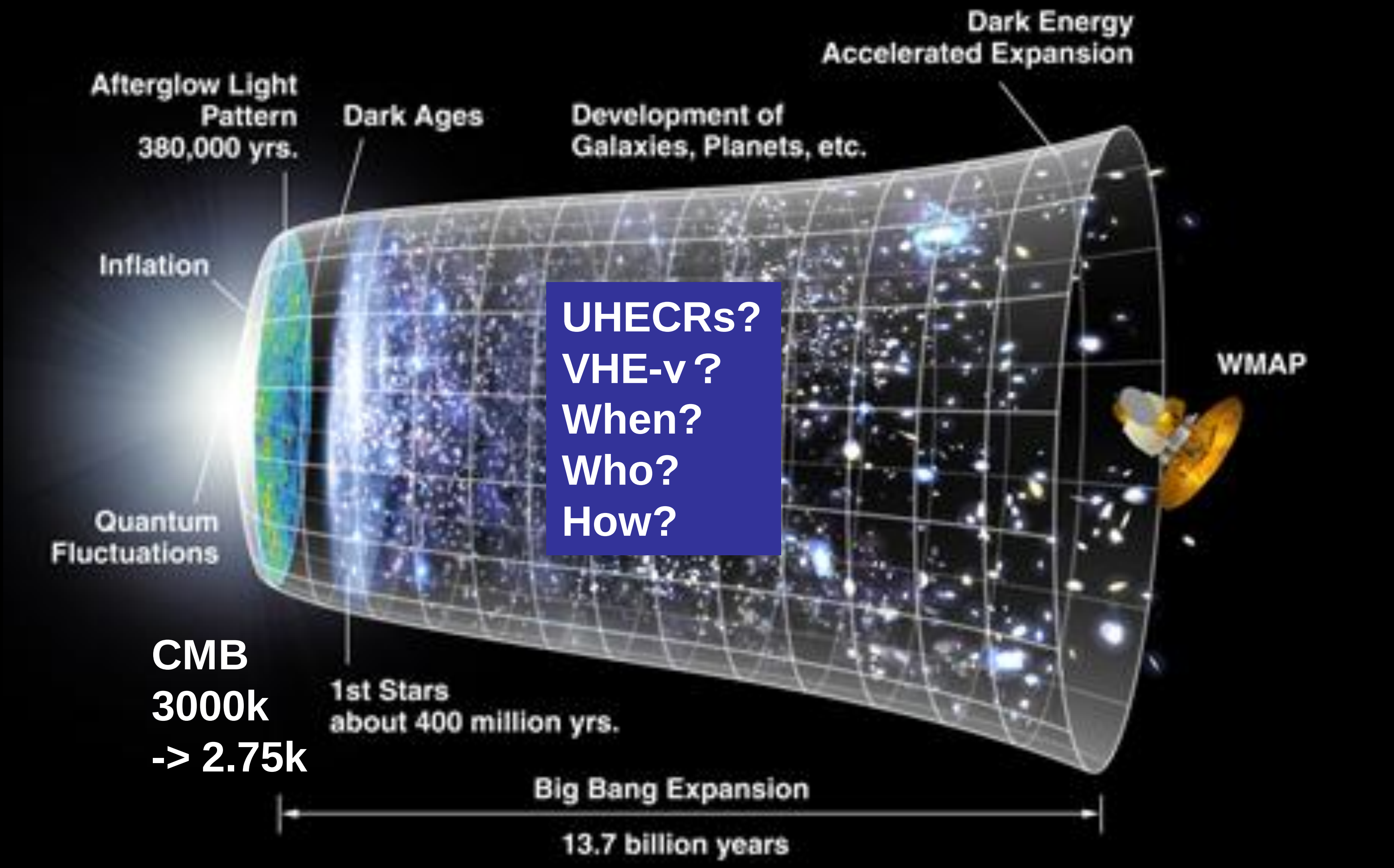
高エネルギーニュートリノ: 理論的な理解の現状

京都大学基礎物理学研究所
長滝　重博

9th March 2011, ICRR, Tokyo

§ Overview

History of the Universe



UHECRs?
VHE-ν？
When?
Who?
How?

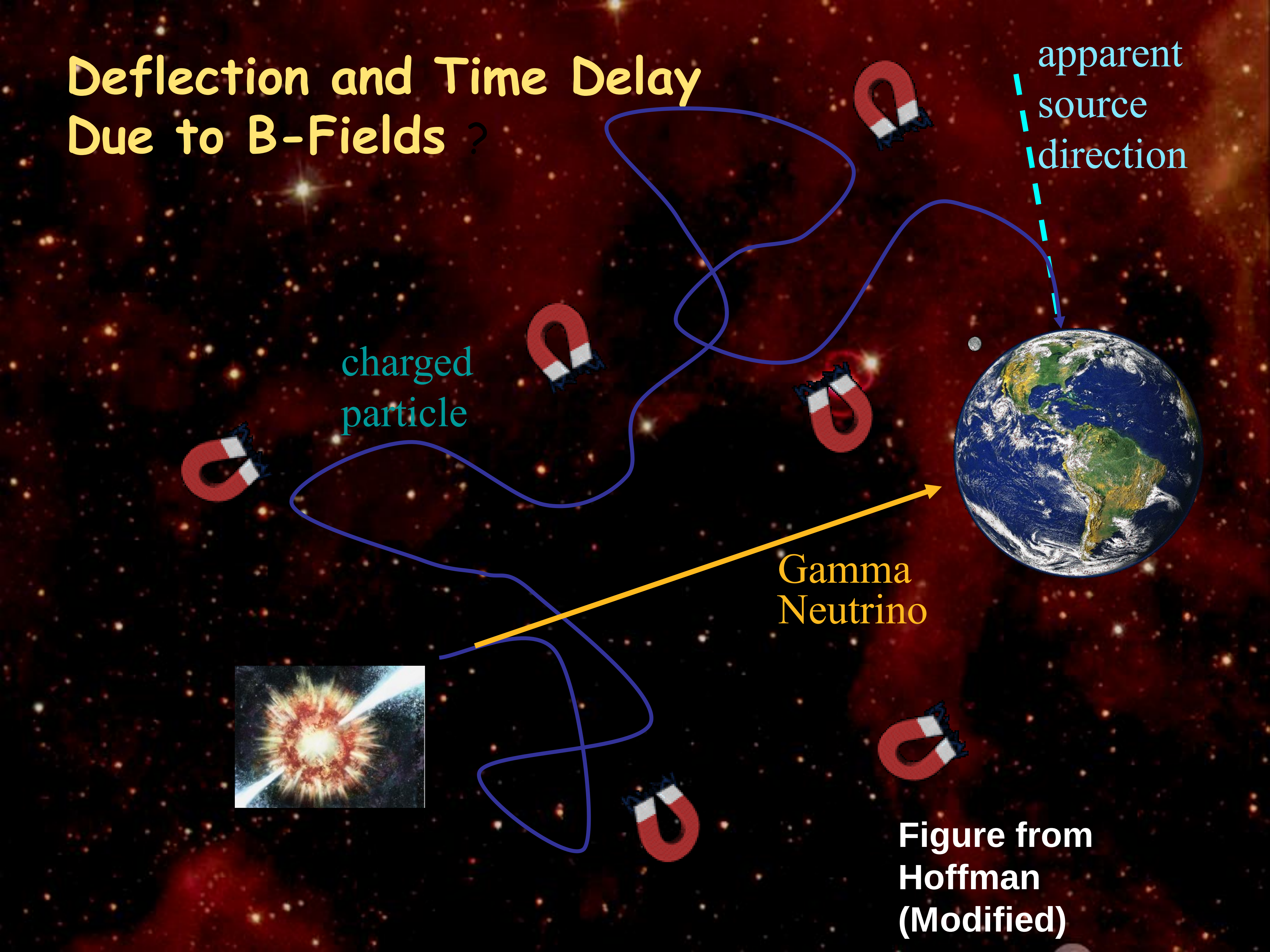
CMB
3000k
-> 2.75k

Mysteries of UHECRs

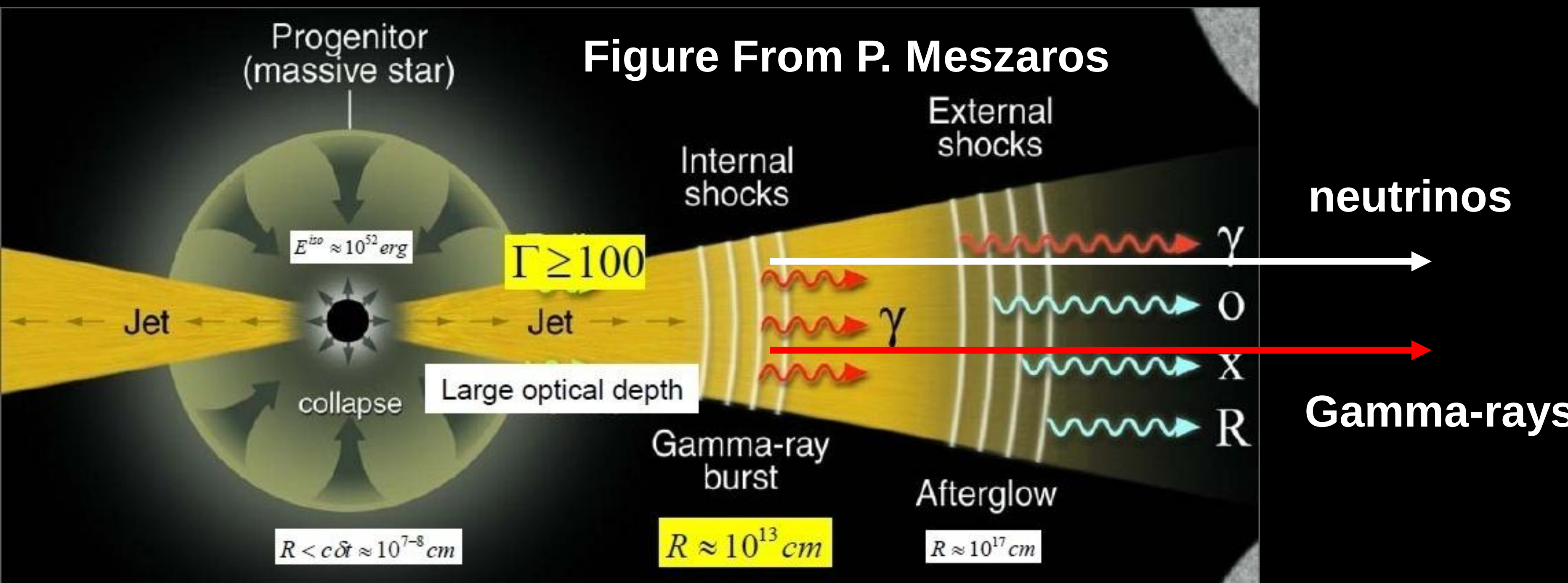
- What are the sources of UHECRs?
- How large is the highest energy of CRs in the universe?
- How are UHECRs produced?
- Composition?

Why Neutrinos?

- ニュートリノはまっすぐやってくる（ソース同定に有効）
  （Answer for “What are the sources of UHECRs?”）
- ニュートリノは遠くからでもやってくる（情報を失わない）
  (Answer for “How large is the highest energy of CRs in the universe?”)
- ニュートリノはハドロン加速を強く支持する。
  (Partially, answer for “How are UHECRs produced?”)
- 宇宙論的ニュートリノ（Cosmogenic Neutirino）は極高エネルギー宇宙線の組成情報を与える。
  (Answer for “Composition?”)
- 他（素粒子的見地、Multi-Messengerの一員、。。。）。


Deflection and Time Delay
Due to B-Fields ?
apparent
source
direction
charged
particle
Gamma
Neutrino
Figure from
Hoffman
(Modified)

Neutrinos come straightly from their sources with (almost) speed of light



GRBからの高エネルギーニュートリノはガンマ線バーストと同時刻、同方向からやってくる（完全なソース同定）。

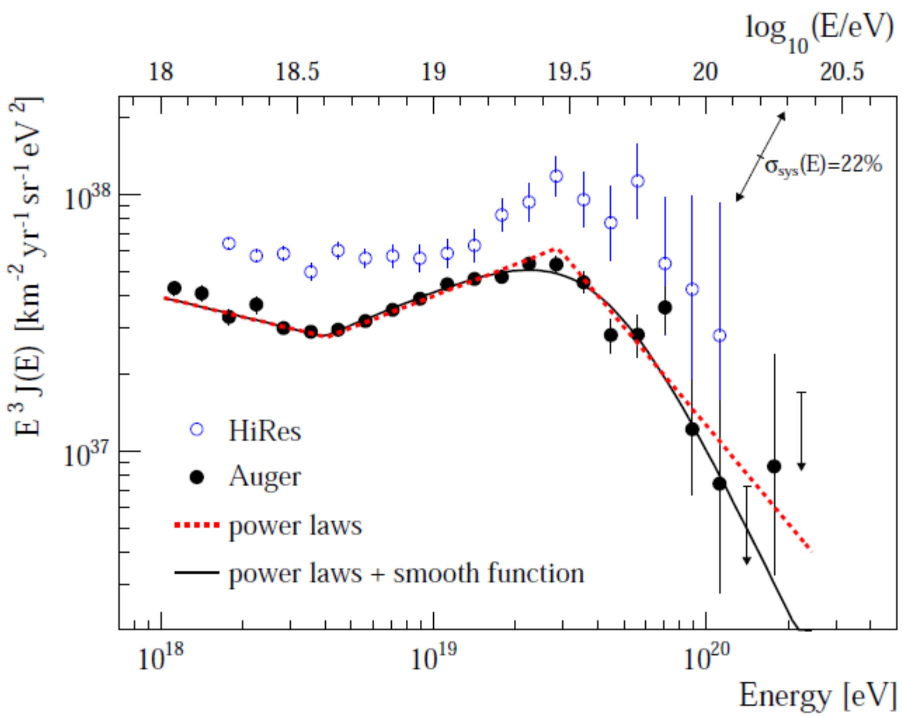
比較：大気ニュートリノのイベントレート
結論：バックグラウンドフリー

$$J^{A}_{\nu\to\mu} \simeq 4\times 10^{-3}\left(\frac{\Delta\theta}{0.5^o}\right)^2\left(\frac{E}{100\mathrm{TeV}}\right)^{-\beta}\ \mathrm{km}^{-2}\mathrm{yr}^{-1},$$

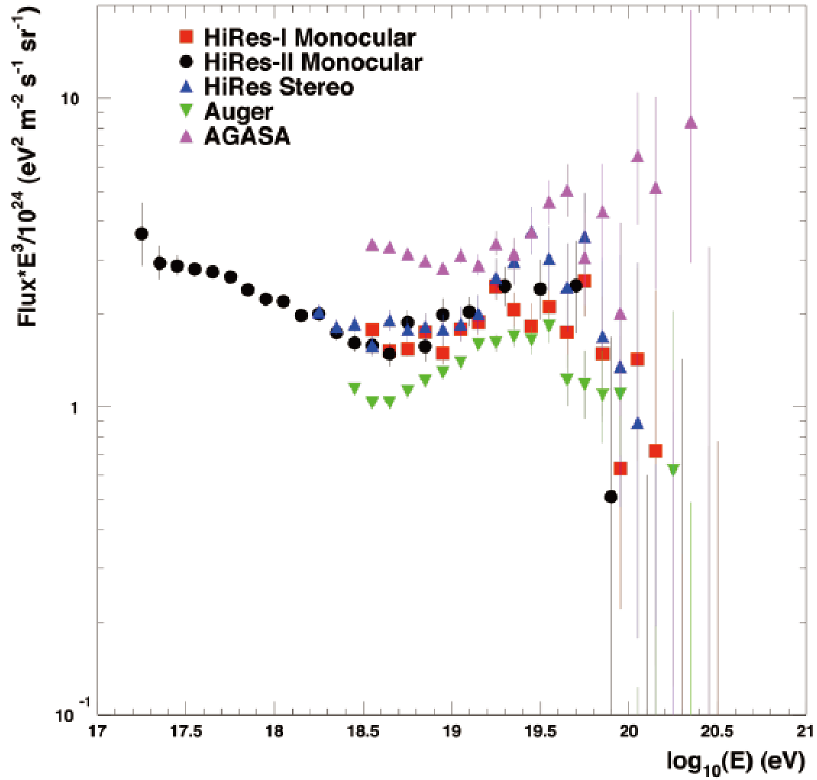
with $\beta = 1.7$ for $E < 100$ TeV and $\beta = 2.5$ for $E > 100$ TeV.

Waxman 2011

ニュートリノは遠くからでもやってくる(情報を失わない): 1
(Answer for “How large is the highest energy of CRs in the universe?”)



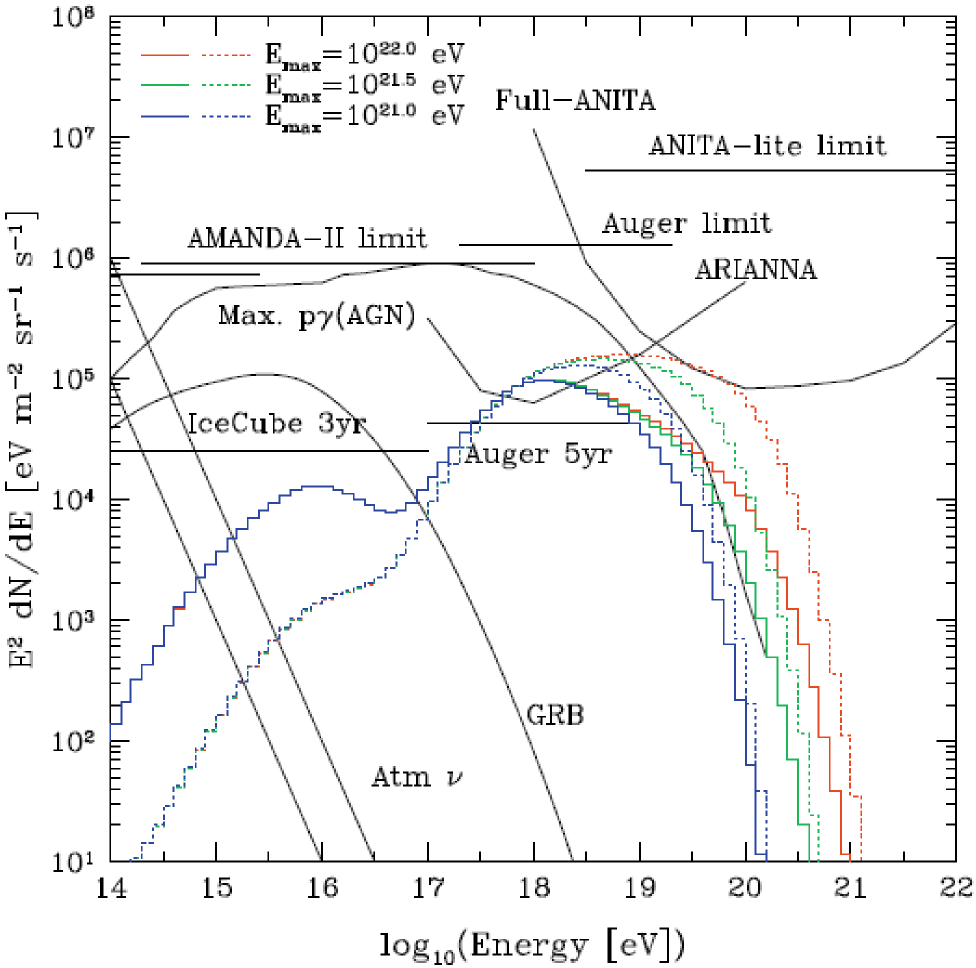
Auger Collaboration 10
More than 20 sigma.



HiRes Collaboration 10

カットオフがあると、どこまでスペクトルが伸びているか判断しずらい。

ニュートリノは遠くからでもやってくる（情報を失わない）: 2
(Answer for “How large is the highest energy of CRs in the universe?”)

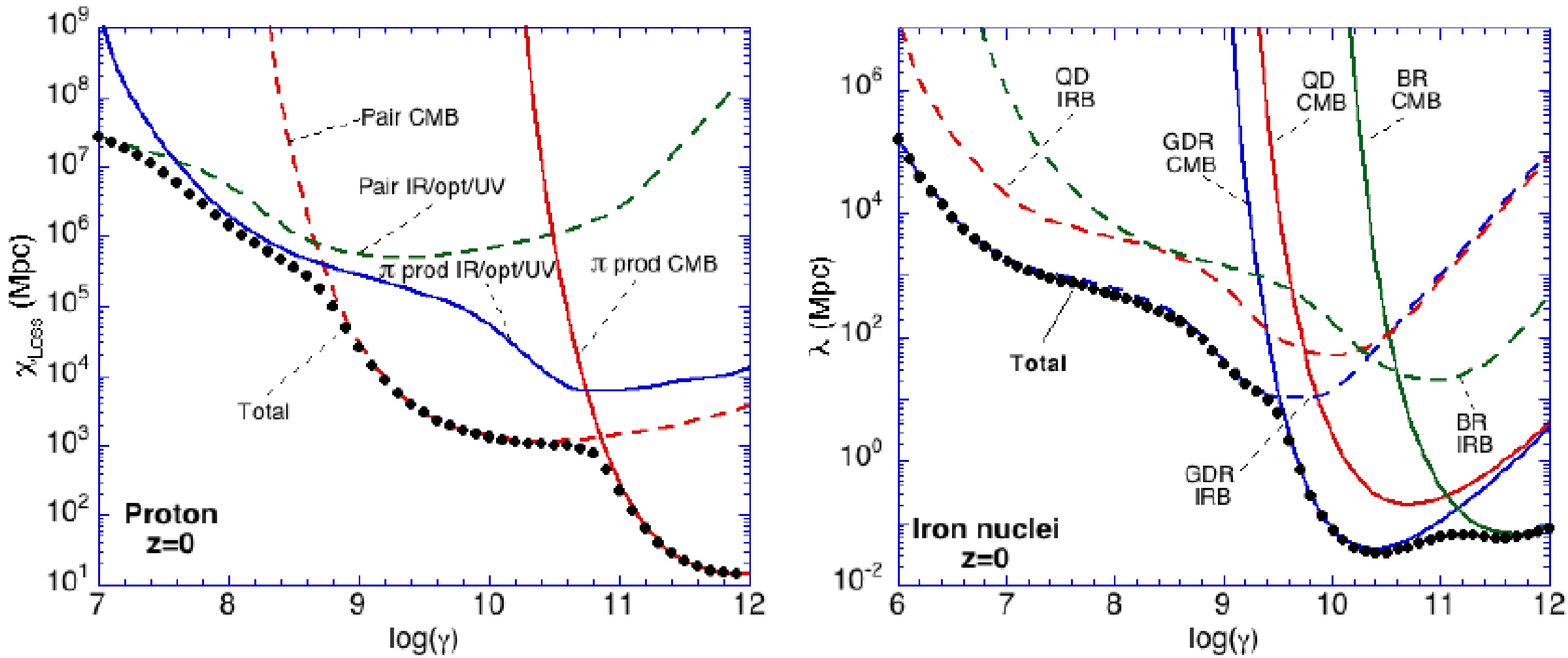


もちろん観測の
困難と表裏一体
ではある。

Cosmogenic Spectrum by Takami, Murase, S.N., Sato 2009

Cosmogenic Neutrinoは陽子起源

Allard+06



陽子のケース。実線（赤、青）のプロセスでニュートリノ作る。

鉄のケース。緑のプロセスでニュートリノ作る。が、タイムスケールが他のプロセスより遅い。

Cosmogenic Neutrino受けたら、親粒子は陽子（但しトップダウンを別途排除する）。
レプトン過程ではニュートリノ生成は無視出来るレベル（ex. 超新星残骸）

- Hunting the Sources, How?

単体ソースか背景放射(diffuse background)か

- 単体ソースからのイベント数。

  F=Flux [個/cm^2/sec] = N[個]/4πD^2/Δt。

  イベント数=F × Δt_{obs} × F_{eff} 。

  F_{eff}は検出効率。
- もしイベント数 > (1かつノイズレベル)なら、単体ソースからのイベントが期待出来る。
- もしイベント数< (1またはノイズレベル)なら、

  多数のソースを見て、確率的に検出するしかない（背景放射）。

単体ソースからのイベント例

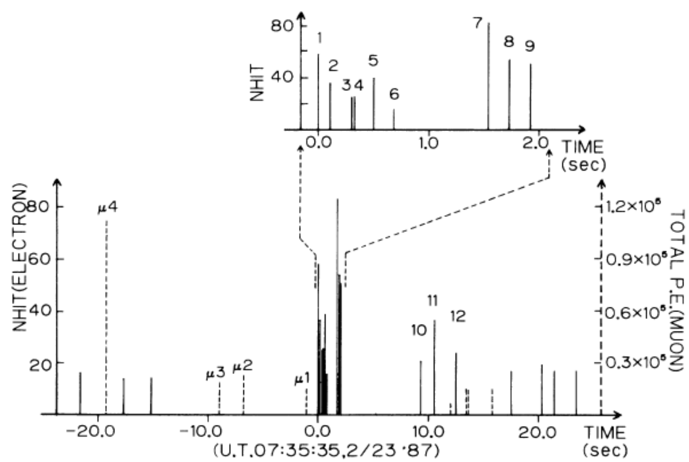
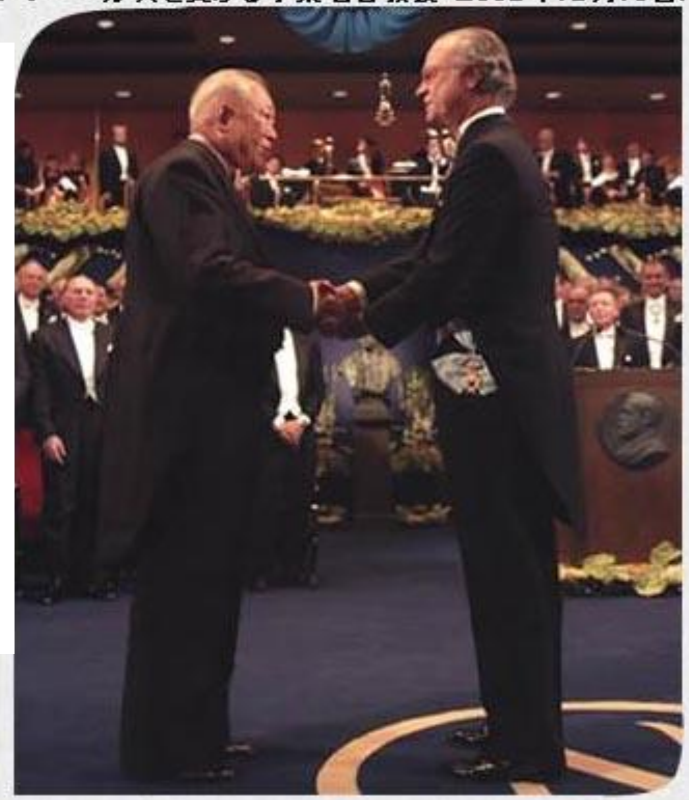


FIG. 2. The time sequence of events in a 45-sec interval centered on 07:35:35 UT, 23 February 1987. The vertical height of each line represents the relative energy of the event. Solid lines represent low-energy electron events in units of the number of hit PMT's, N_{hit} (left-hand scale). Dashed lines represent muon events in units of the number of photoelectrons (right-hand scale). Events $\mu 1-\mu 4$ are muon events which precede the electron burst at time zero. The upper right figure is the 0–2-sec time interval on an expanded scale.

Hirata et al. 1987 PRL

▼ ノーベル賞を受ける小柴名誉教授 (2002年12月10日)

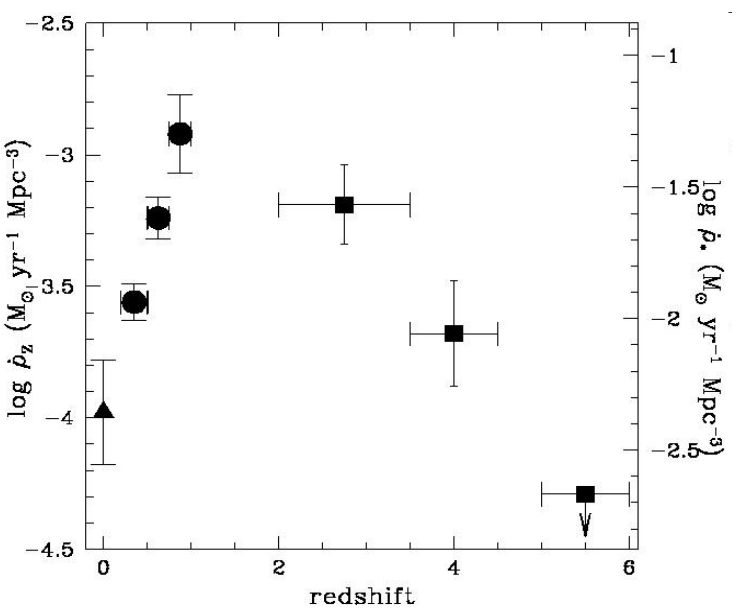


背景放射の例

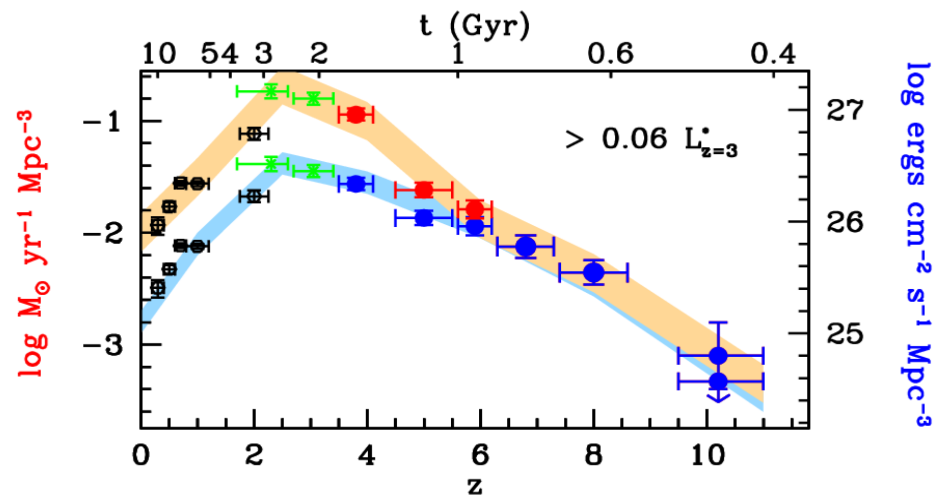
- 超新星背景MeVニュートリノ （SN1987Aは特別であった）。
- その他、大抵の高エネルギーニュートリノ候補天体（GRB, AGN, 銀河団、Starburst銀河、。。。）。
- 背景ニュートリノの場合、どの距離の天体からのニュートリノが最も受かりそうか？
- 背景ニュートリノは一様か？

背景ニュートリノの場合、どの距離の天体からのニュートリノが最も受かりそうか？

- F=Flux [個/cm^2/sec] = N[個]/4πD^2/Δt。
- 天体の数∝D^3。
- 期待されるイベント数∝D。遠いものから受かる確率が高い！
（単体イベントのケースと真逆。最近でもCen Aについて議論あり）
- ただし天体の数はある距離以降は減る(z～1-2位。3Gpc)。



Madau 1998

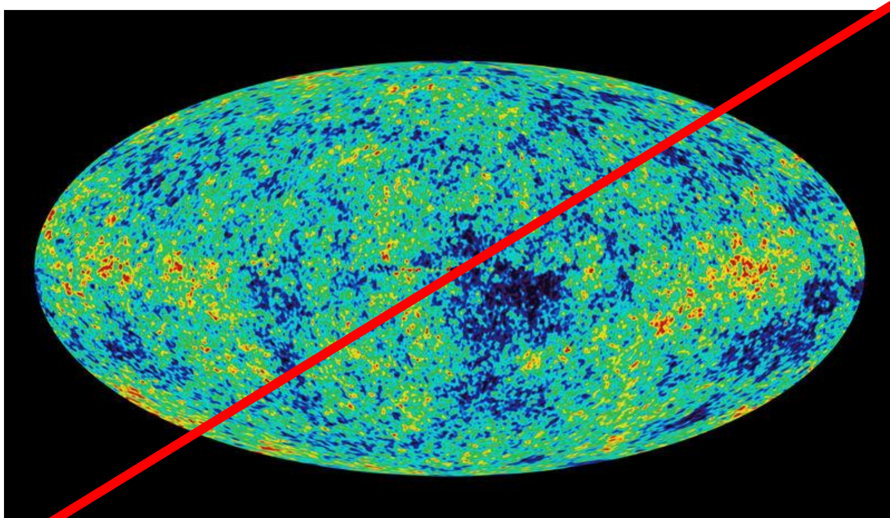


Bouwens et al. 2011

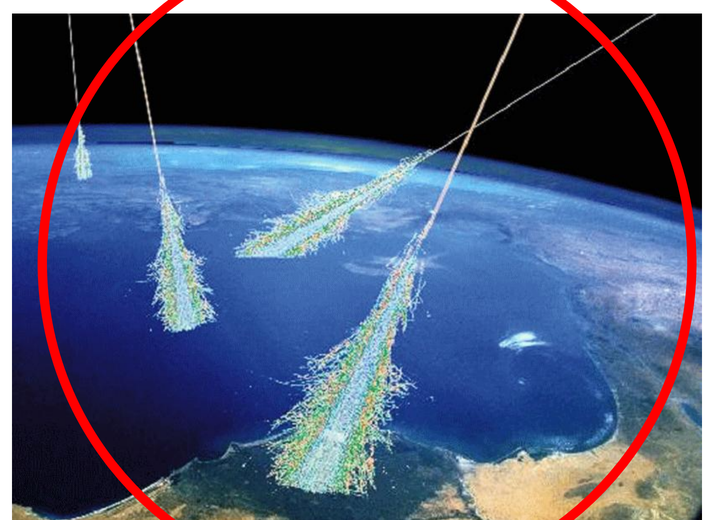
背景ニュートリノは一様か？

- 背景のソースによる。
- ニュートリノの分布は、(おおまかに言えば)対応する光の分布にほぼ同等（例：超新星の残光とMeV-Neutrino、GRB (VHE-)GammaとVHE-Neutrino）。

GRB VHE-Neutrinoの場合は。。。

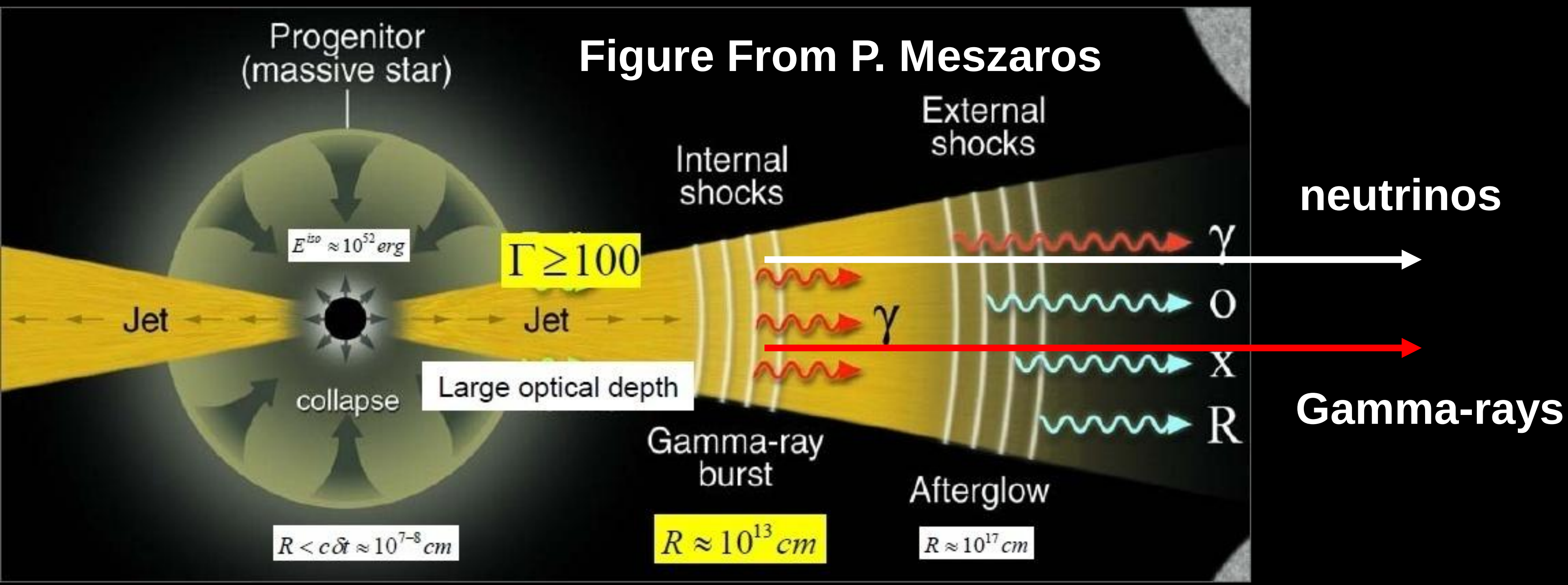


WMAP



寺澤さんHPより

ガンマ線バースト背景ニュートリノ



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Waxman 2011

§ 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 constraint exists)

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

Acceleration mechanism：Shock Acceleration.

Emission mechanism：P-gamma or PP for protons.

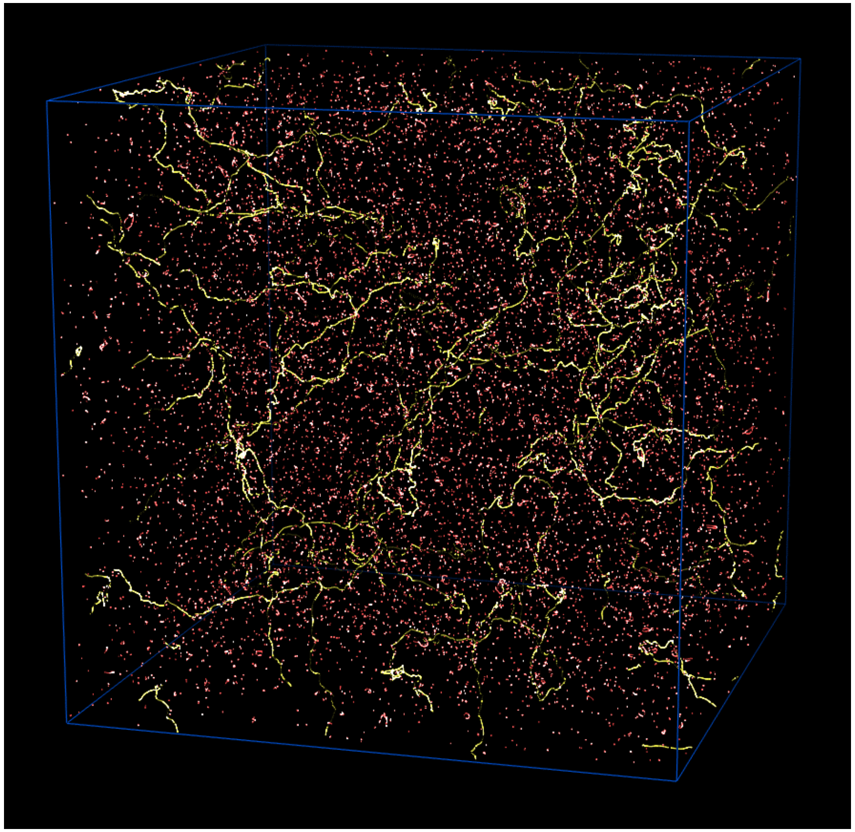
Compositions：Proton (some times, Nuclei)

常に、Cosmic Rayの総量を手で与える（フラックスの高さを手で決める）。（第一原理計算でなく）観測からこの高さを決める(推定する)のが、近未来に於いても最も可能性が高い (ex. Cosmogenic Neutrino)。

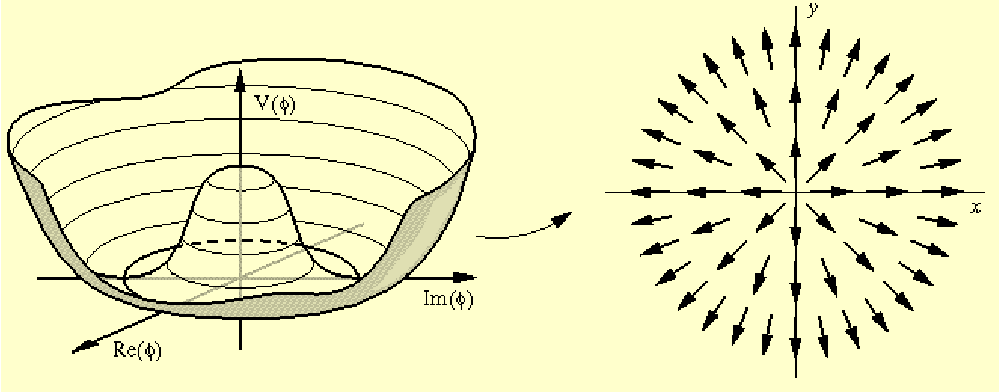
- Top-down Scenario, or Bottom Up Scenario?

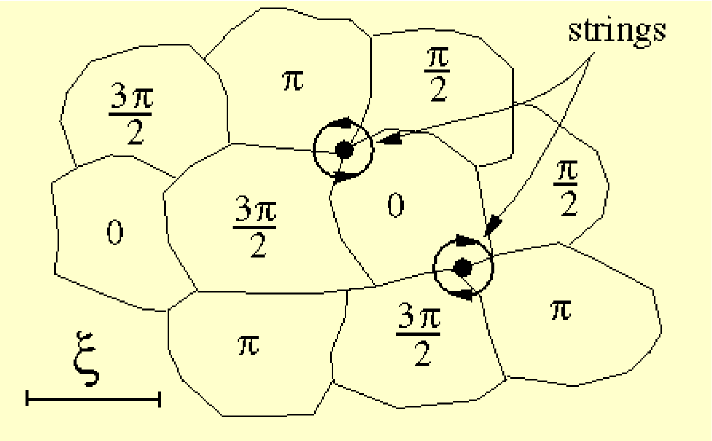
Top-down Scenario？

- Long-lived, super-heavy particles?
- Cosmological Defect?



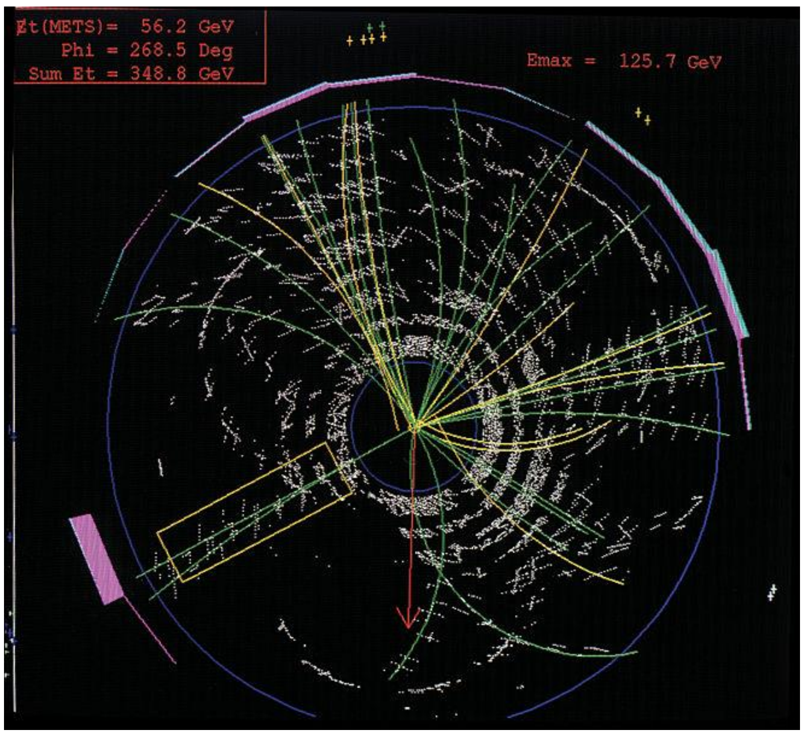
Simulation of Cosmic String
(Cambridge Cosmology Group HP)



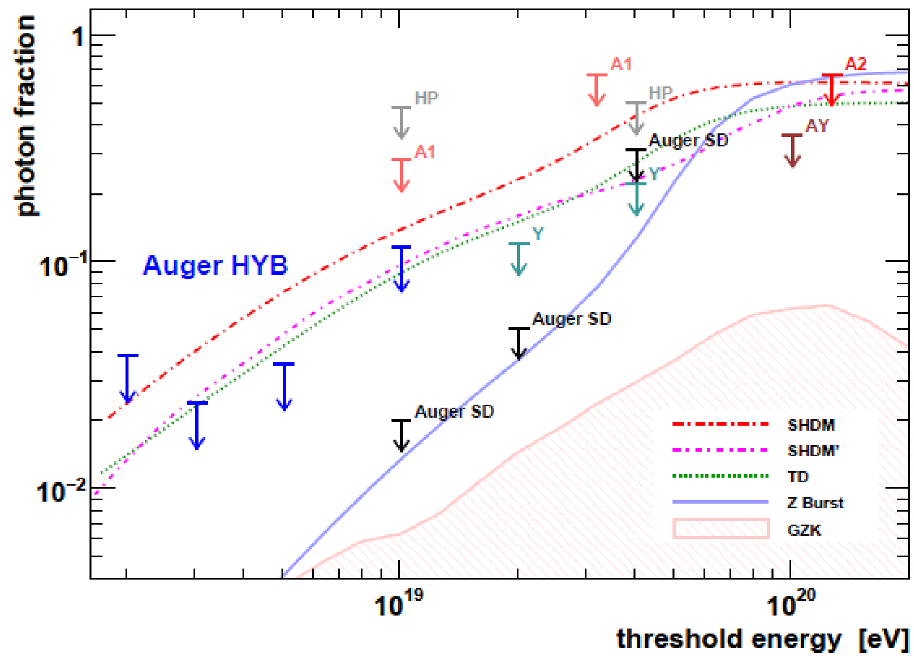


Decay of Super-heavy particles/Cosmic String

- (N-quark+N-lepton) are assumed to be born.
- Their Cascades.
- Resulting Particles are mainly Gamma-Rays and Neutrinos.

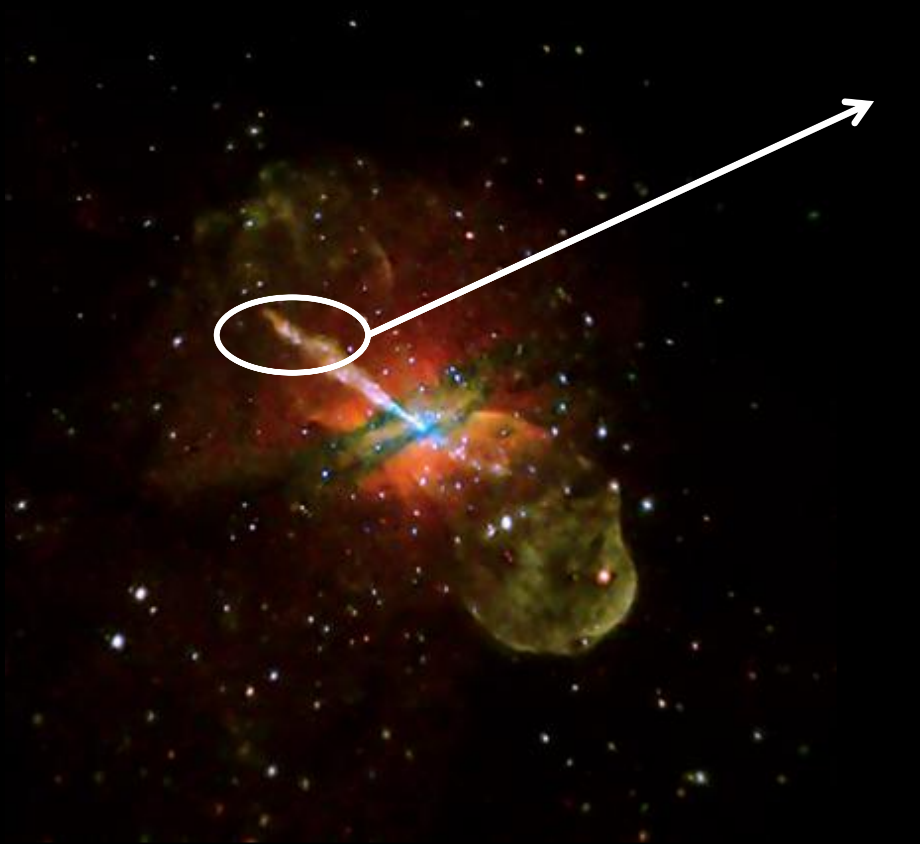


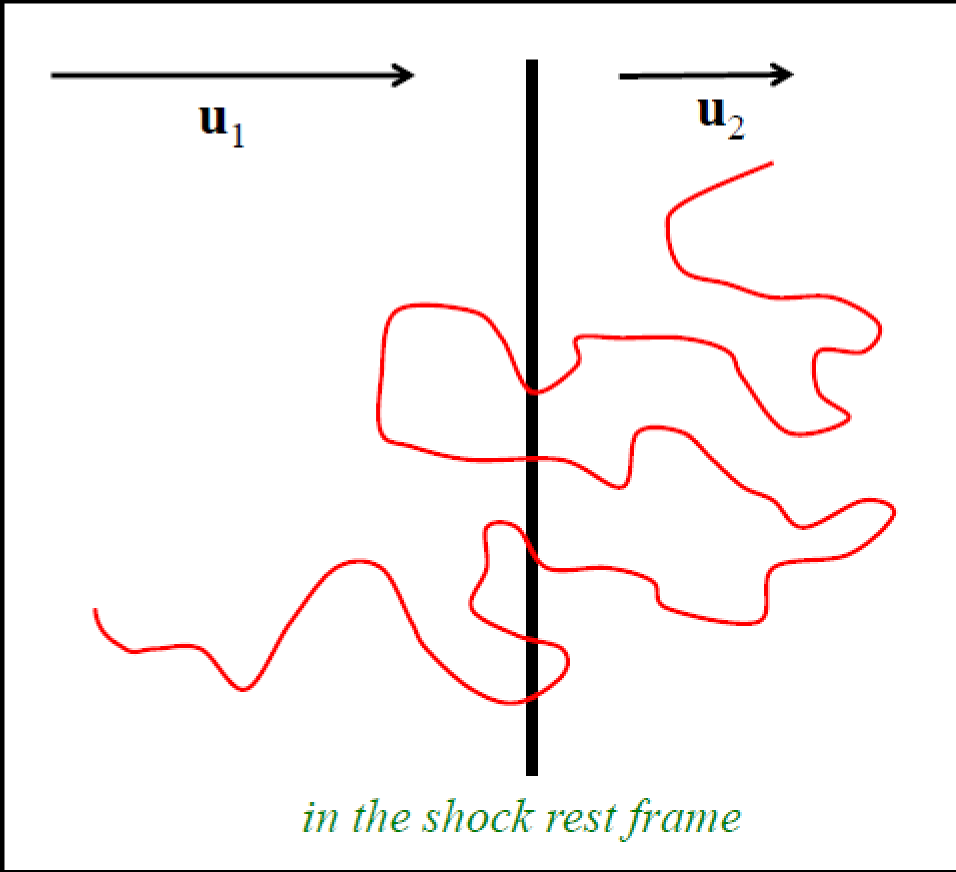
Jets from Top-quark and anti-top quark (by Tevatron).



Fraction of primary photons (from PAO collaboration, 2009)

Particle Acceleration at Shock

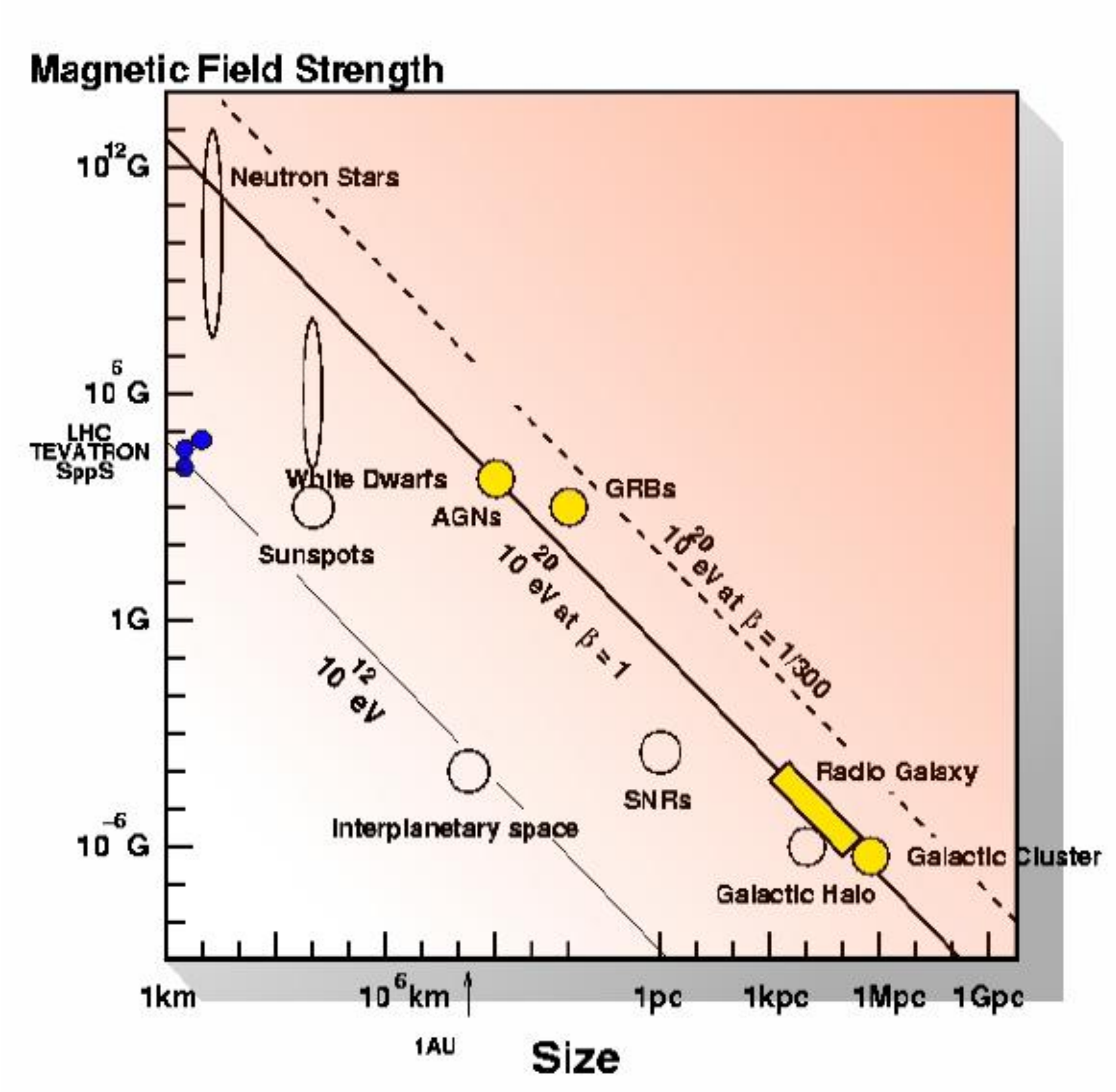




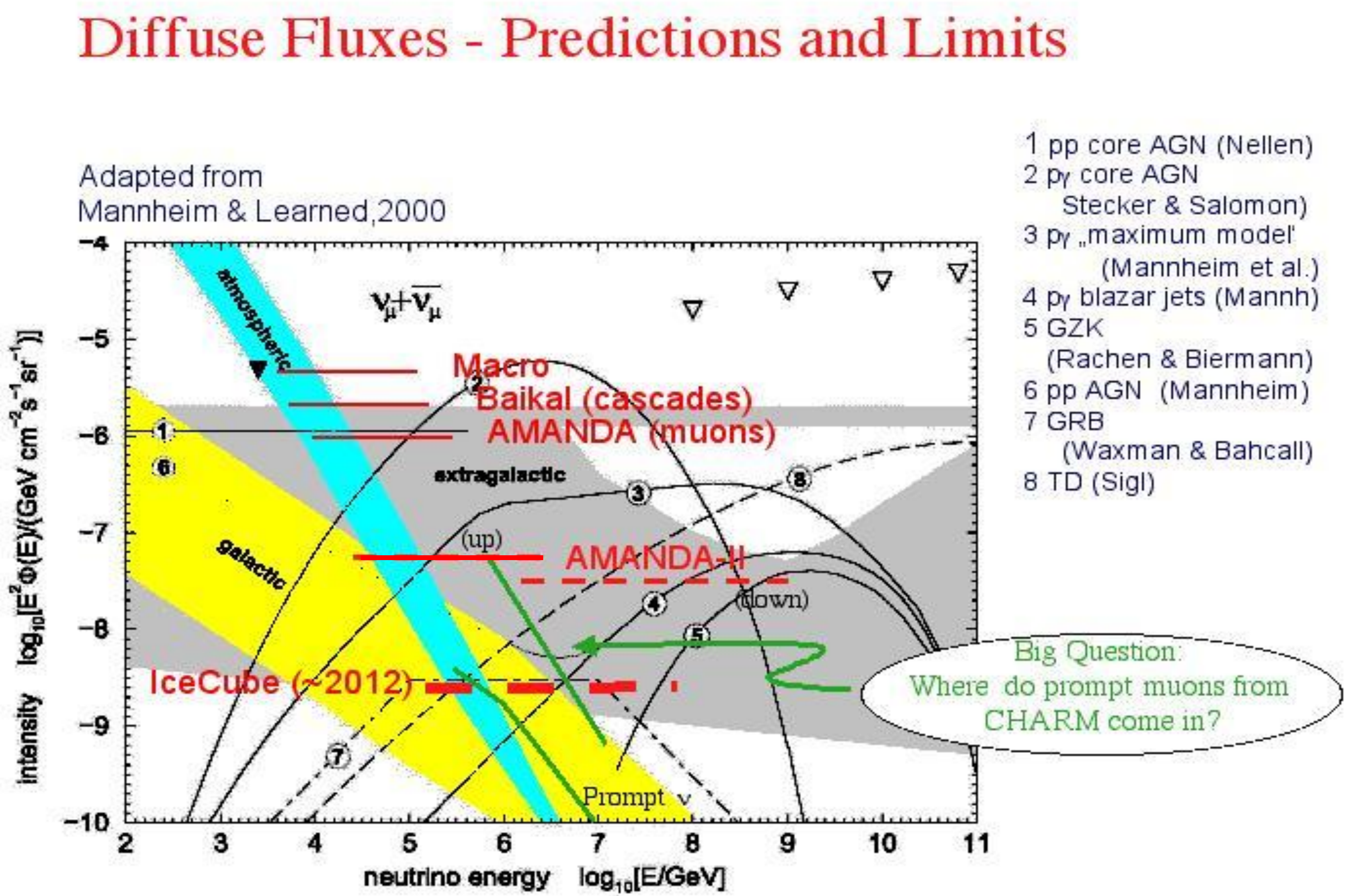
Active Galactic Nuclei: Centaurus A

Bottom-Up Scenario

Hillas Diagram



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

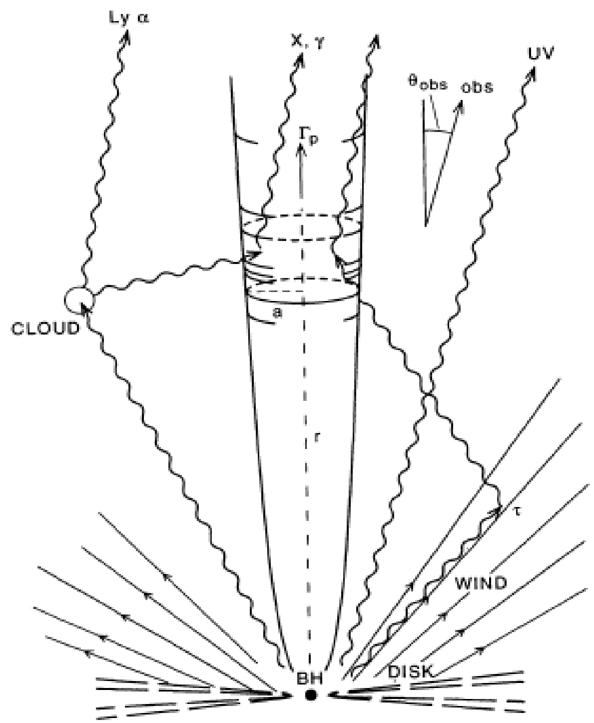
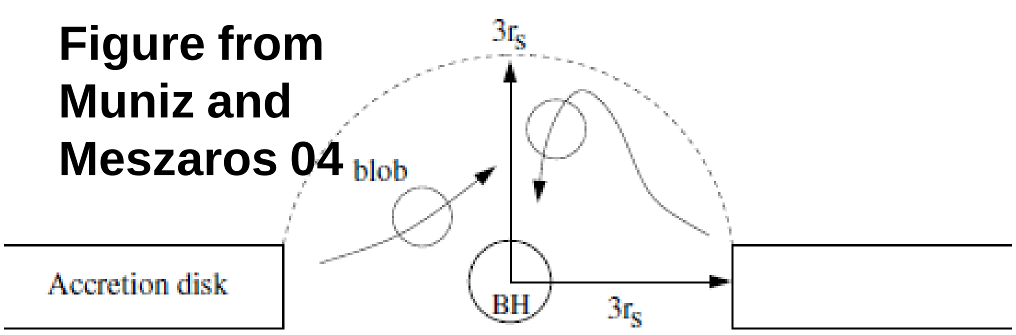


FIG. 2.—Geometry of the source. The radiating region, denoted by short cylinder of dimension *a*, moves along the jet with pattern Lorentz factor Γ_p. Underlying flow moves with Lorentz factor Γ, which may be different.

Figure from Muniz and Meszaros 04



AGN Jet models:
Shocks in the Jet

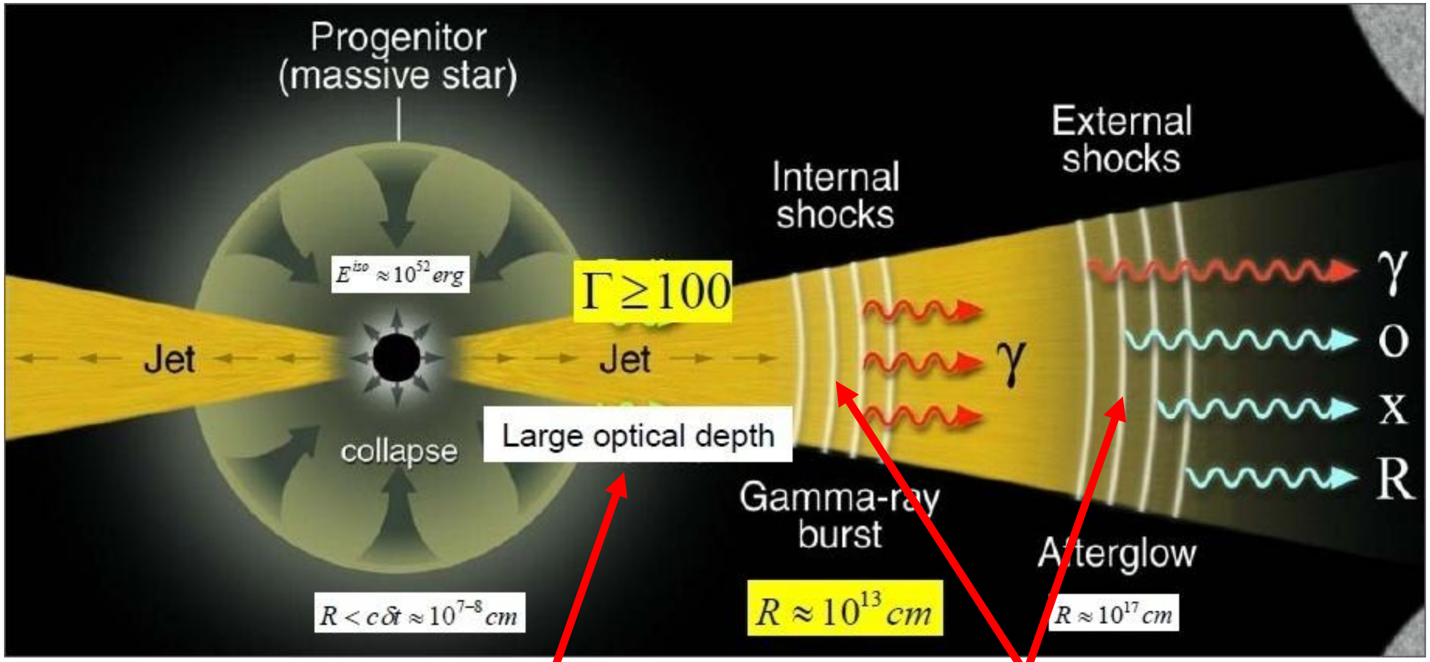
Optically thin models.

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

内側からは多量の低エネルギーニュートリノが出る、外側からは少量の高エネルギーニュートリノが出る。外からはUHECRsが逃げ出しているかもしれない。



Optically thick models.

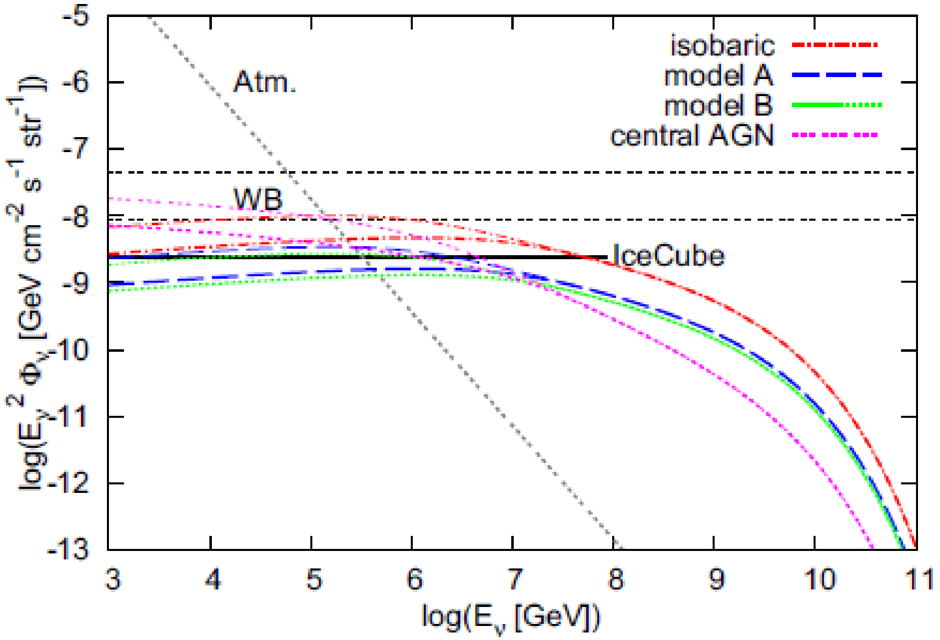
Optically thin models.
UHECRsを同時に説明しようとしたりする。

Murase and S.N. 06a,06b; Murase,Ioka,S.N.,Nakamura 06,08;
Iocco, Murase,S.N.,Serpico 07

Source Candidate 3: Cluster of Galaxies

Cambridge HP

Murase, Inoue, S.N. 08



See also
Kotera, Allard, Murase, Aoi, Dubois, Pierog, S.N. 09
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

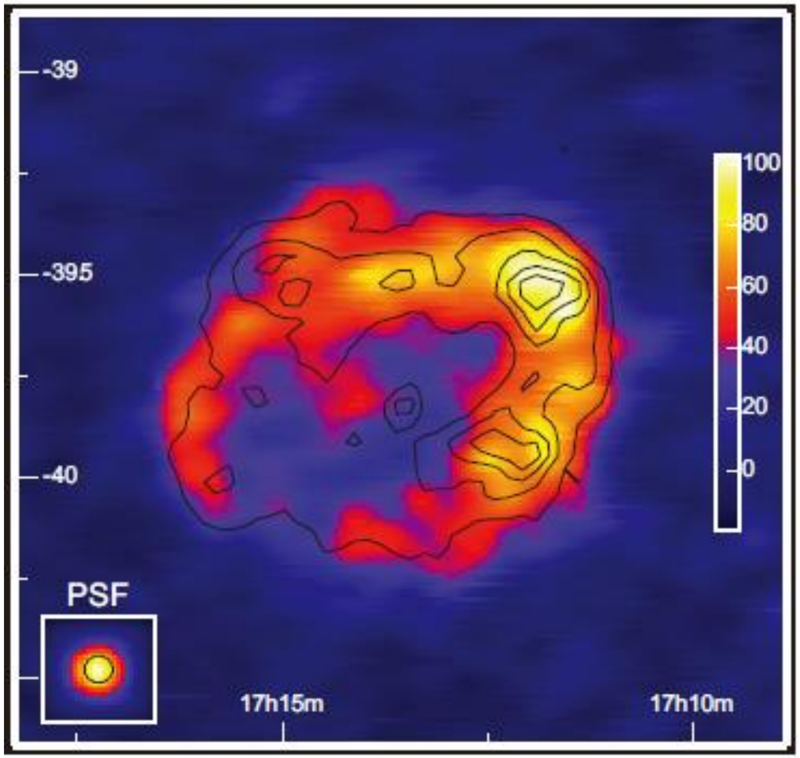


Image of RX J1713.7-3946
Color：HESS
Contour：ASCA（1- 3keV）
Aharonian+06
PP interactions, optically thin.

Lee, Kamae, Ellison 2008

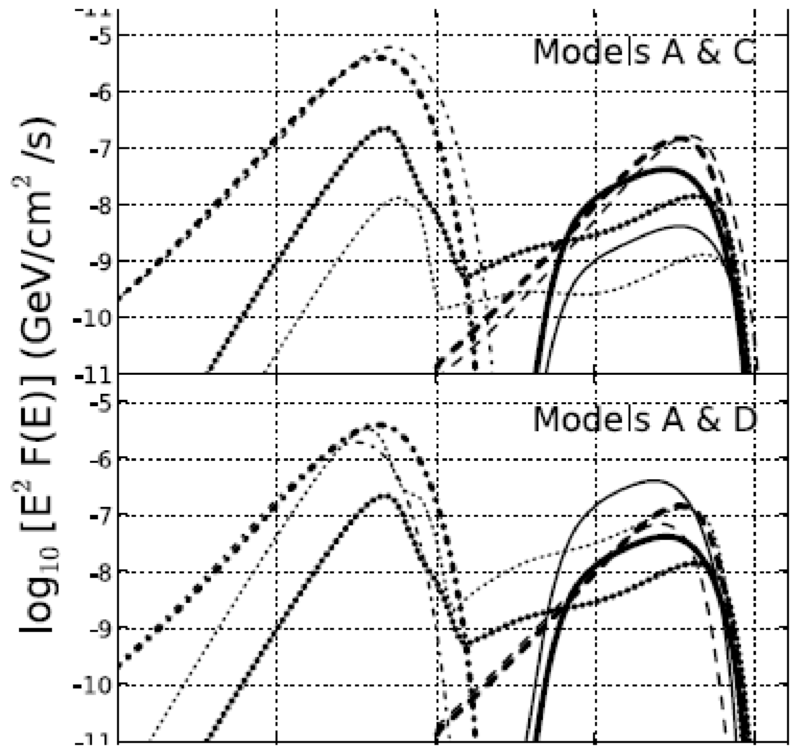


FIG. 5.—Photon spectra of all four models integrated over the region from the CD to the FS. *Top three panels*: Models B to D are compared to model A and are split into individual components for different emission mechanisms: π^0-decay (*solid line*), IC (*dashed line*), bremsstrahlung (*dotted line*), and synchrotron radiation (*dash-dotted line*). Thin lines represent spectra for model B, C, and D in each panel, while model A is shown as bold lines. *Bottom*: The contributions from all mechanisms are summed for each model: model A (*thick solid line*), model B (*thin solid line*), model C (*dashed line*), and model D (*dash-dotted line*).

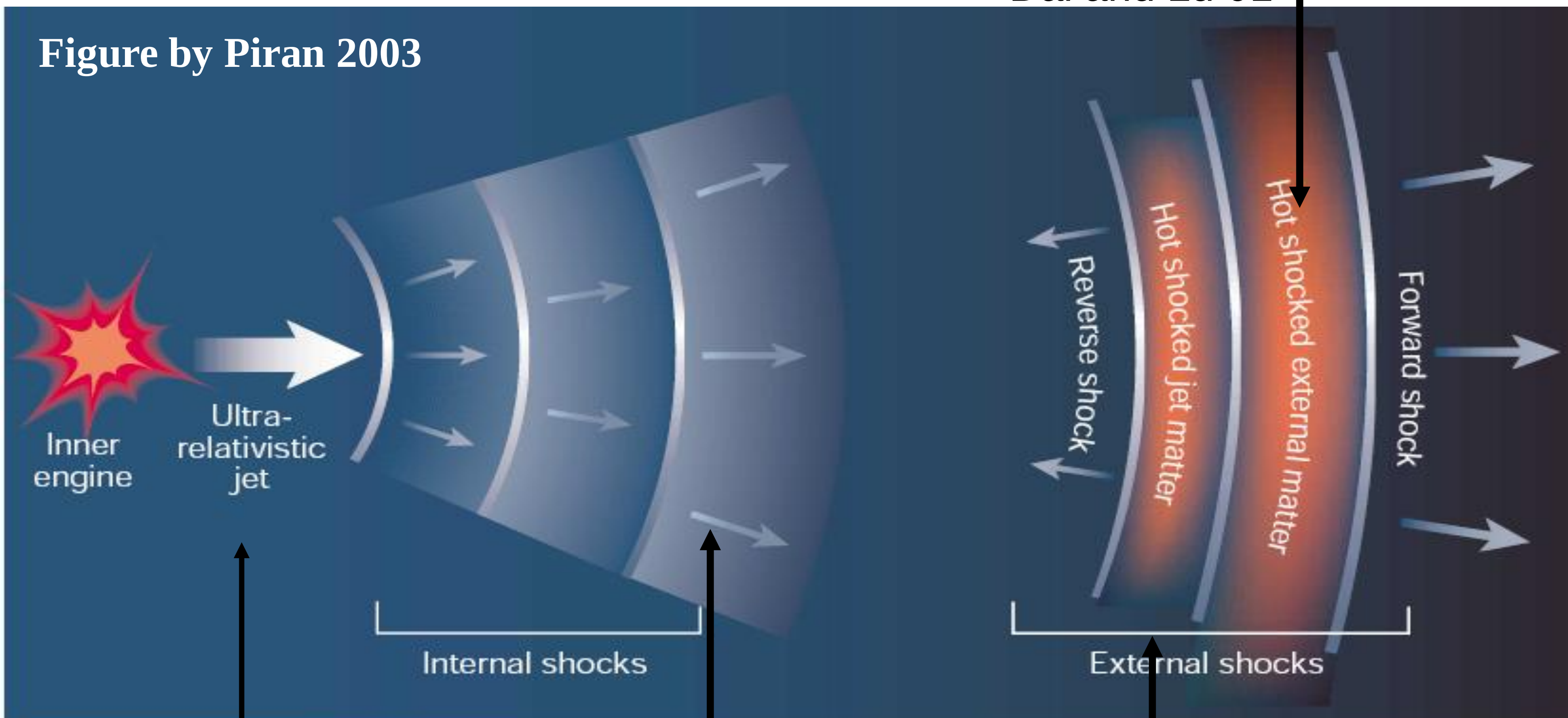
§ Method of Estimation of VHE neutrinos: Case of GRBs

手順はAGNs, Starburst Galaxies, Cluster of Galaxiesなどでも同じ。

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
Iocco,Murase,S.N.,Serpico 08

GeV-TeV Neutrinos

Waxman and Bahcall 97
Murase and S.N. 06a,b

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

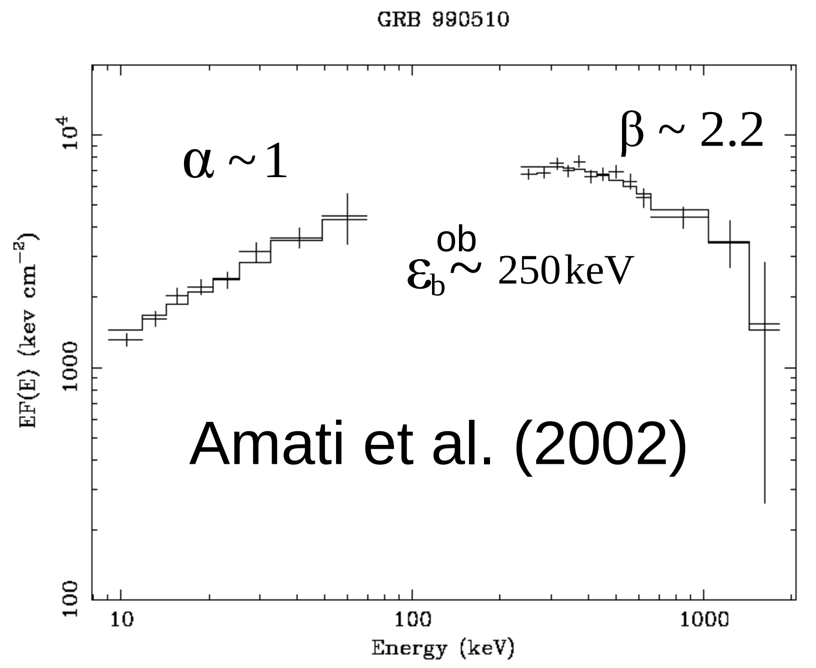
Energy density of gamma-rays (it is X-rays in the fluid rest frame) in the fluid rest frame depends on the $E^{iso}_{\gamma,tot}$ and location of the internal shocks.

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

: 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 Eγ,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 $$t_d \sim r_d / \gamma c$$

rd 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 pγ interactions $p + \gamma \rightarrow \Delta \rightarrow n + \pi^+$ $\kappa_p \sim 0.2$

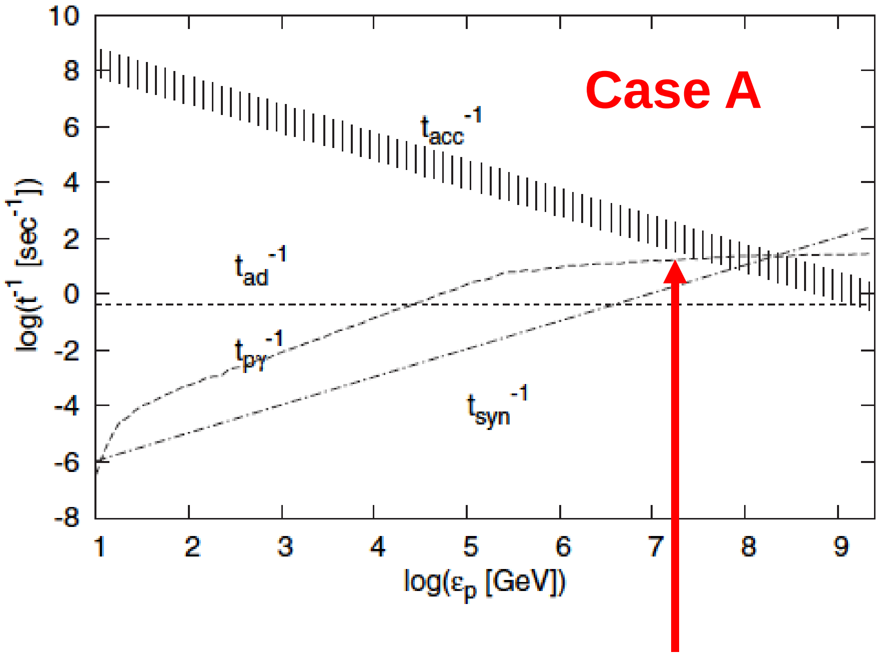
Calculated by Geant4

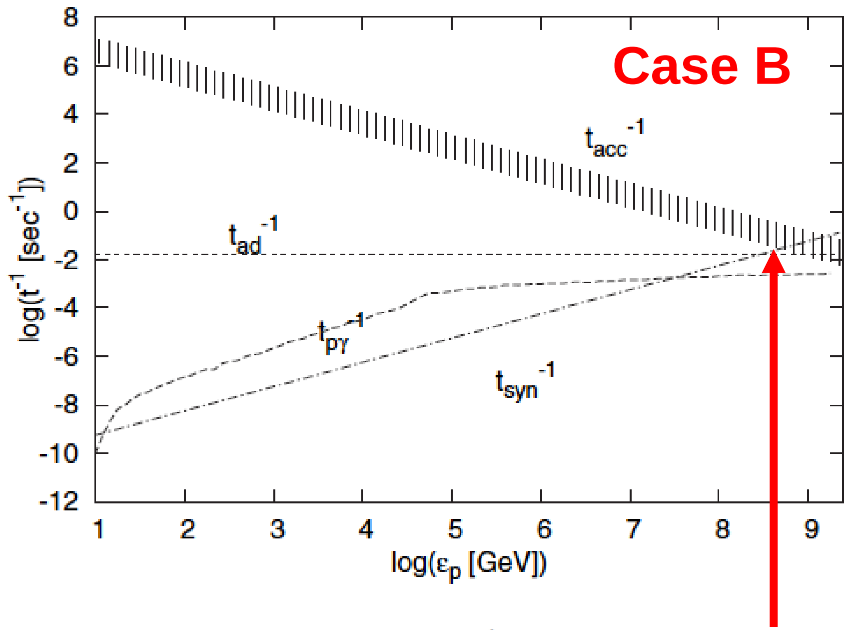
$t_a < \min(t_d, t_{sy}, t_{p\gamma})$ **Protons are accelerated when this condition is satisfied**

$t_{p\gamma} < t_d$ **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 Emax 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 $p + \gamma \rightarrow \Delta \rightarrow n + \pi^{+} \quad \kappa_p \sim 0.2$

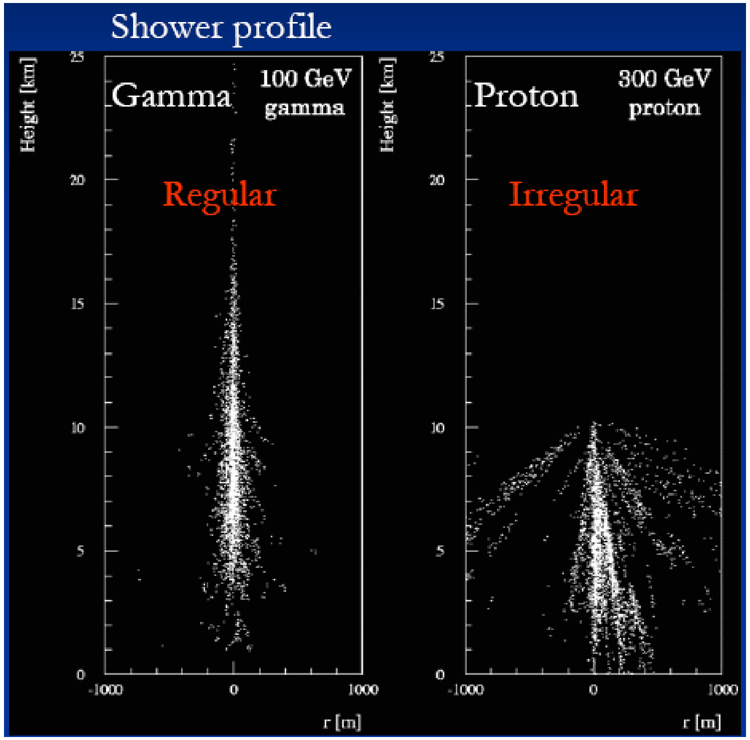
Multi-pion productions $p + \gamma \rightarrow N\pi^{\pm} + X \quad \kappa_p \sim (0.5\text{—}0.7)$

Geant4
Multiplicity + Inelasticity

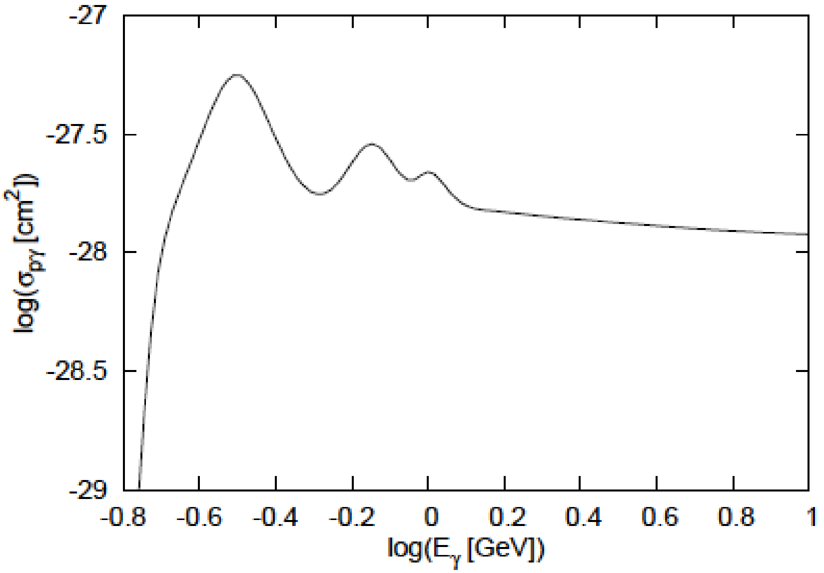
$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu}) \rightarrow e^{\pm} + \nu_{e}(\bar{\nu}_{e}) + \nu_{\mu} + \bar{\nu}_{\mu}$$

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

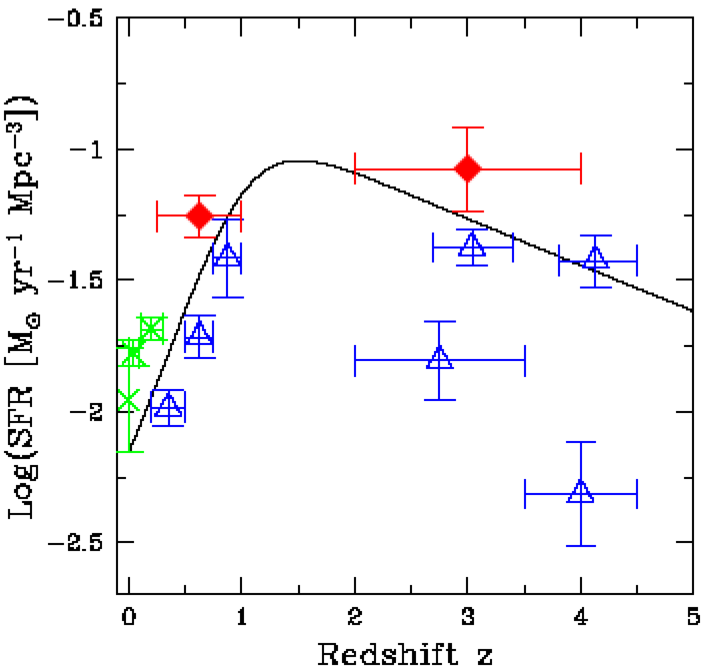
GRB Diffuse Neutrino Background is obtained using the GRB rate history in the Universe.

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

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

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

Assumption: GRB rate ∝ star formation rate (Takami, Murase, S.N., Sato 09)



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

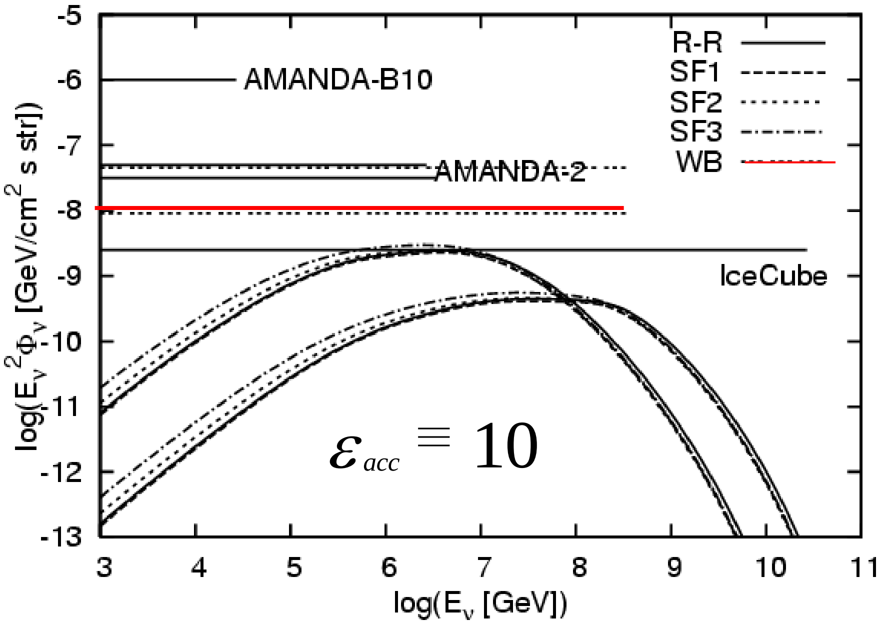
Normalization factor, fcl, is the possibility That a massive star causes a GRB, and Determined by the present GRB rate.

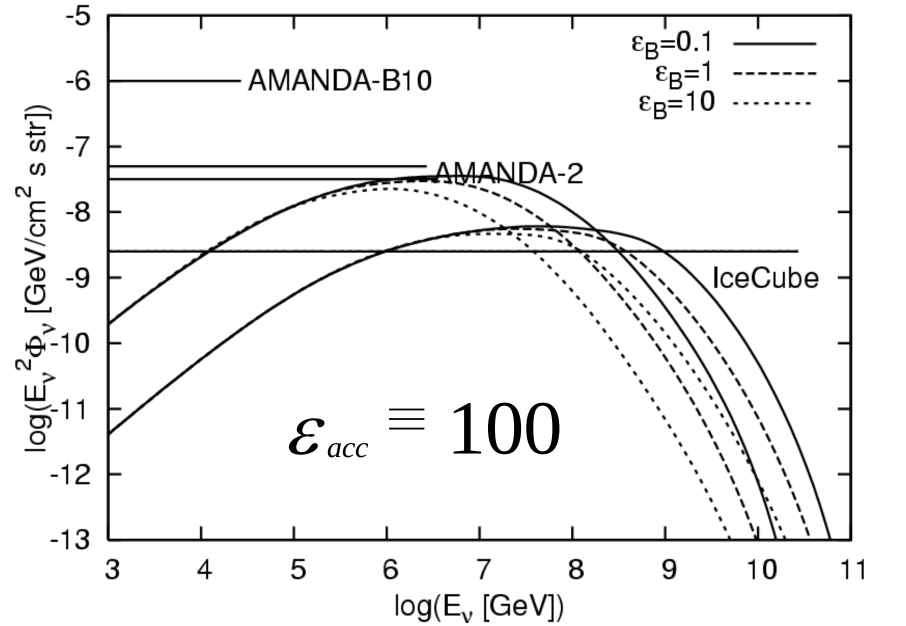
$R_{\rm GRB}(0) = 17 h_{70}^3 \ {\rm yr}^{-1}\ {\rm Gpc}^{-3}$ Shumidt (2001)

⟶ **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.

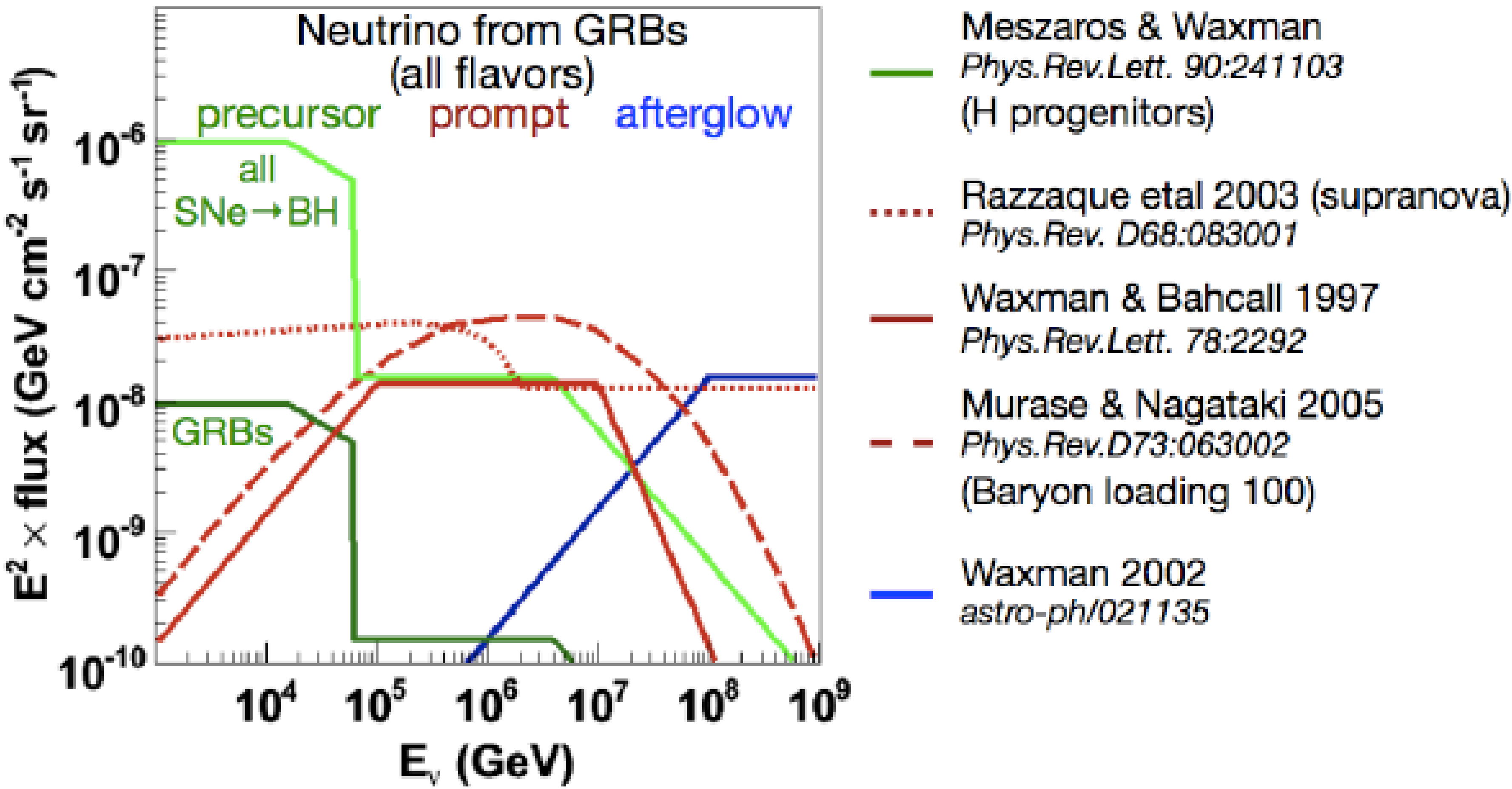
$\varepsilon_{acc} \equiv 10$

$\varepsilon_{acc} \equiv 100$

Event rates@km^2 detector:
Case A: 17 events per yr, Case B: 1.5 events per yr.
Case A: 170 events per yr, Case B: 15 events per yr.
Promising!

GRB neutrino flux predictions

内側からは多量の低エネルギーニュートリノが出る、外側からは少量の高エネルギーニュートリノが出る。外からはUHECRsが逃げ出しているかもしれない。



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**

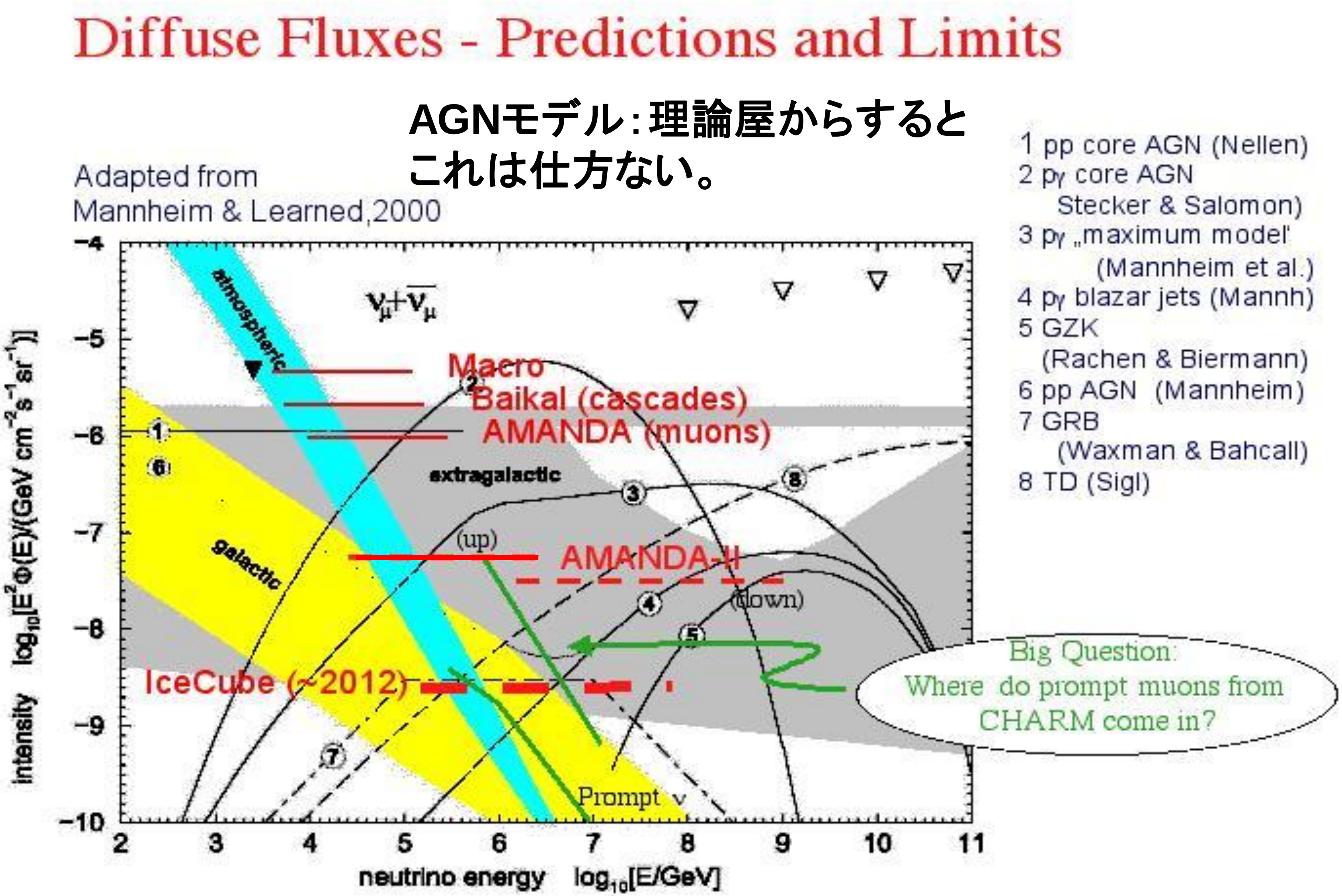
Waxman and Bahcall limit

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).

Expected Diffuse Neutrinos from Various Candidates

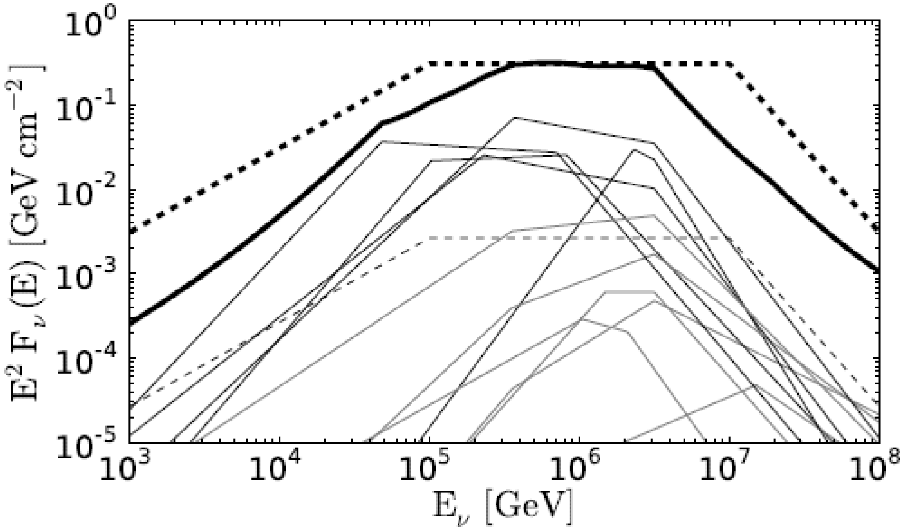
AGNモデル：理論屋からすると
これは仕方ない。



§ Current Status of Observations of AMANDA/IceCube

Limits on GRB-Neutrino by IC40

IceCube Collaboration 2011



観測時間がかかってる。

FIG. 1. The spectra of the five brightest GRBs are shown along with eight randomly selected bursts (thin lines). A single burst with Waxman 2003 parameters[13] is shown by a thin dashed line. The sum of all 117 individual bursts is shown as a thick solid line along with the Waxman 2003[13] prediction in a thick dashed line.

IceCubeにより、（UHECR以上に厳しい）新しい物差しが理論家に与えられだした。
f_π= min(1, $t_d/t_{p\gamma}$)を選びなおさないと、IceCubeとUHECRsを同時に説明できない時代になった。
理論家は、その新しい物差しを使ったり、マルチゾーンを考えたりするだろう。

Arrival Directions of VHE Neutrinos/Muons

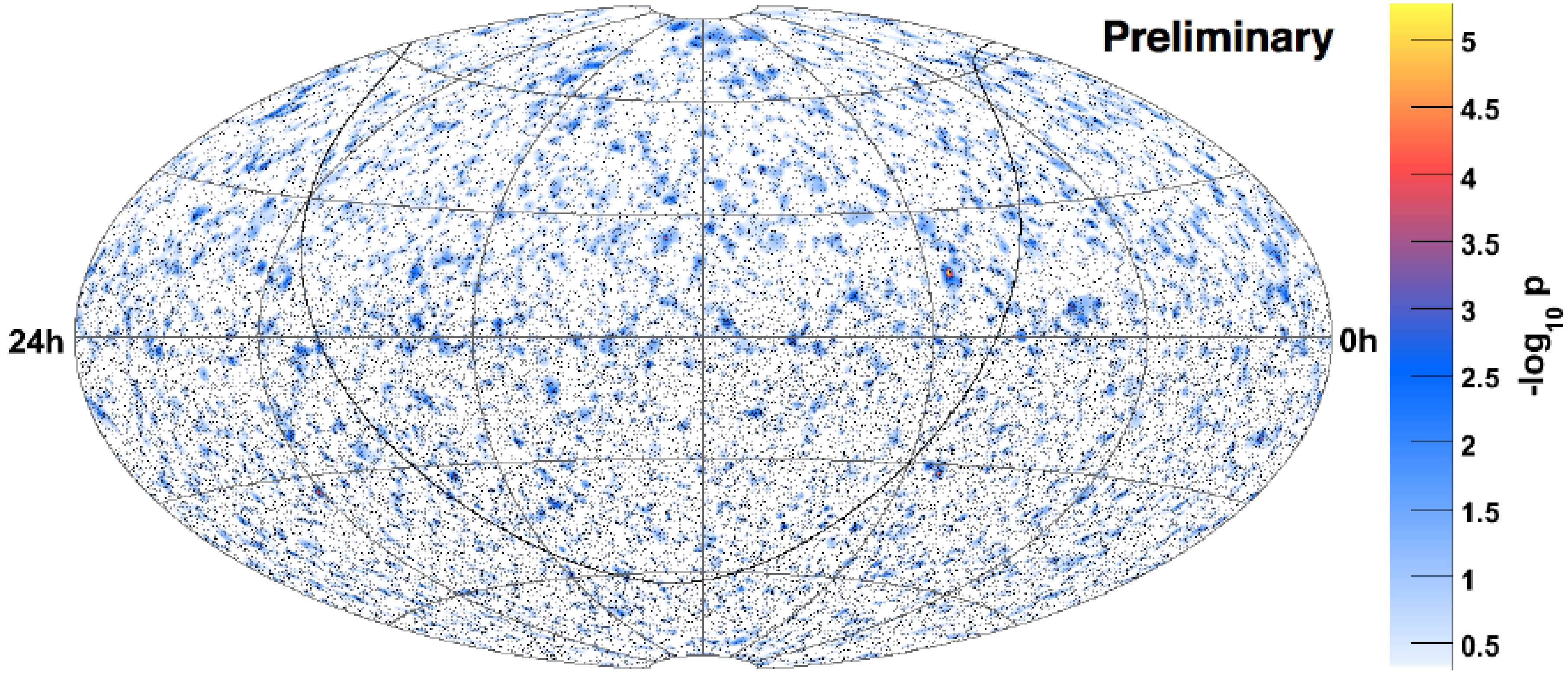


Figure 1. Skymap for the IceCube detector in the 40 string configuration for one year of data taken during 2008.

- New Astronomy driven by VHE Neutrino Detection in the (next?) decade

Resconi プレゼンファイルより

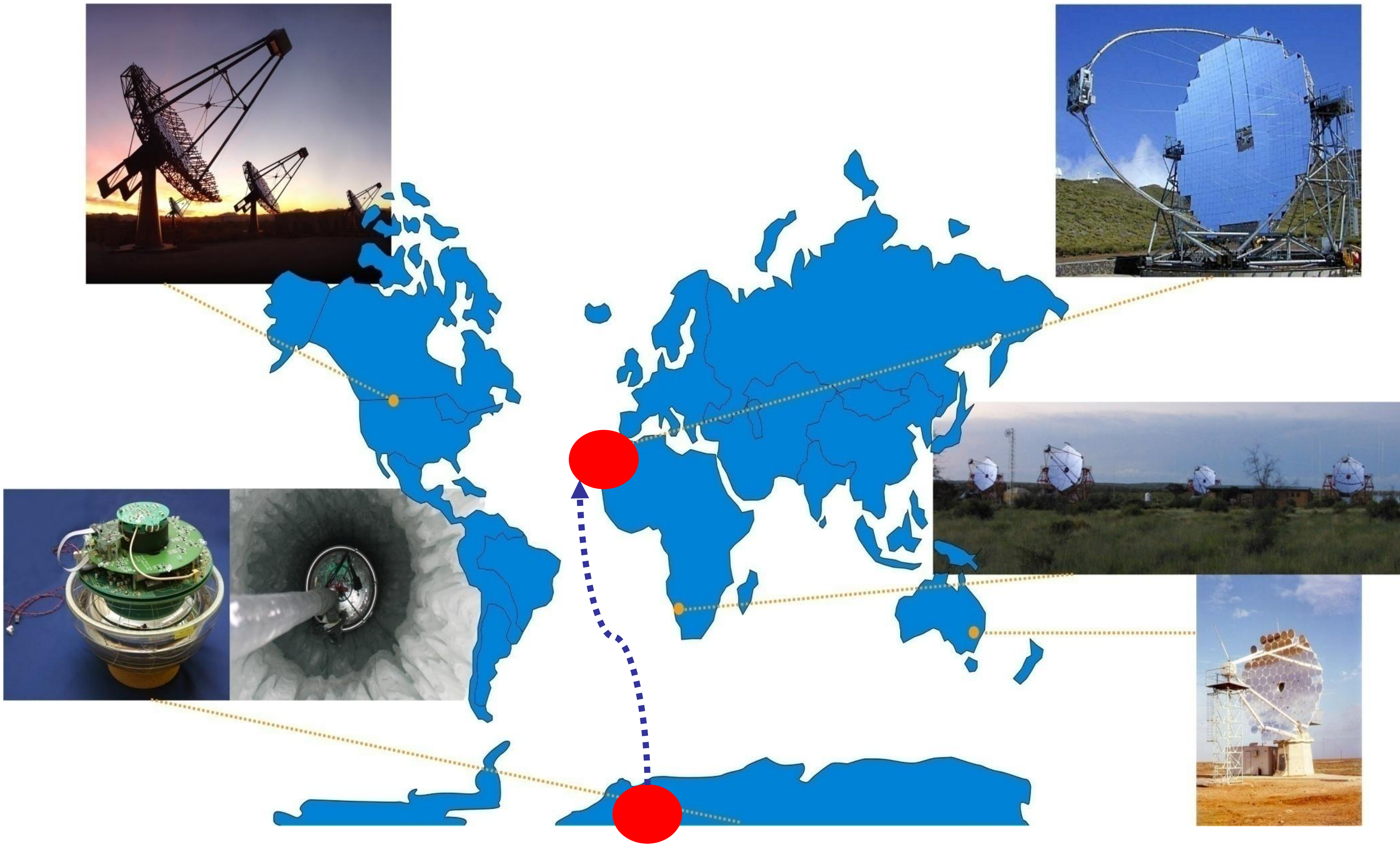
AMANDA – MAGIC

Alerts sent

Reaction within one day

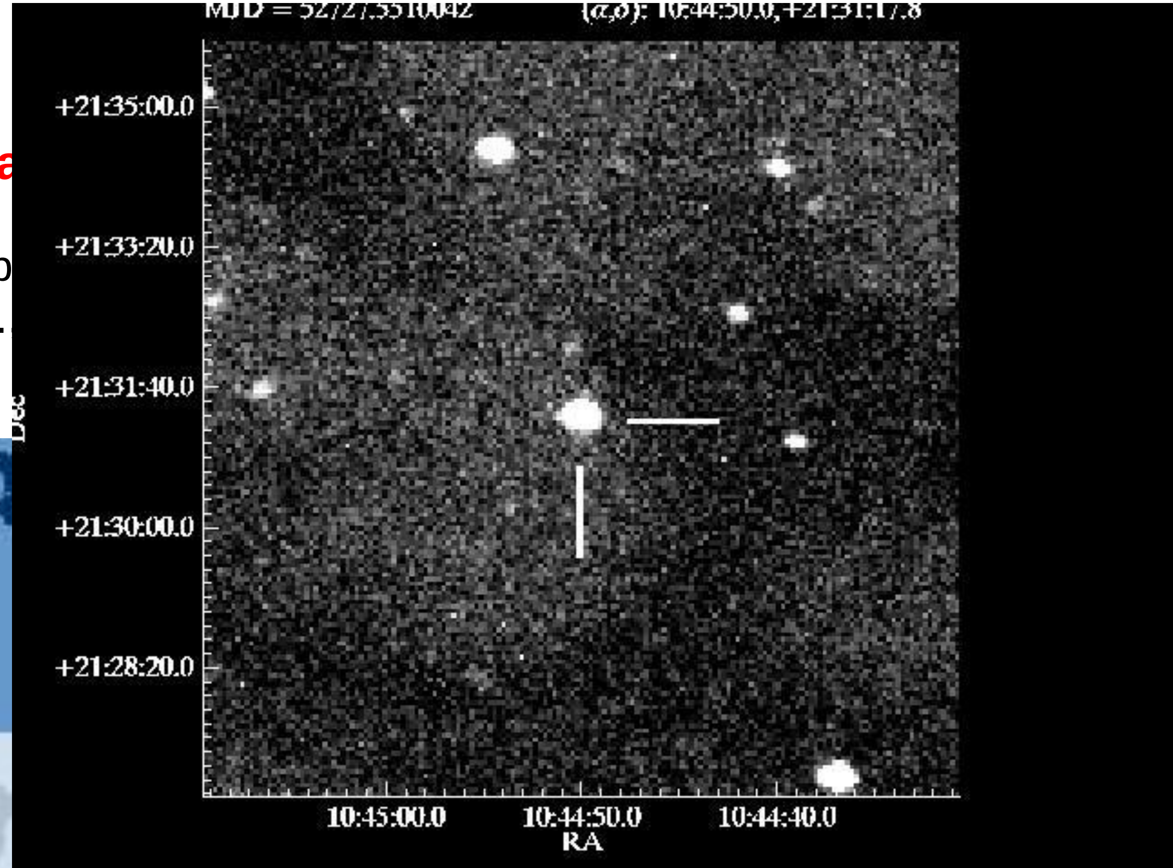
27th September to 27th November 2006

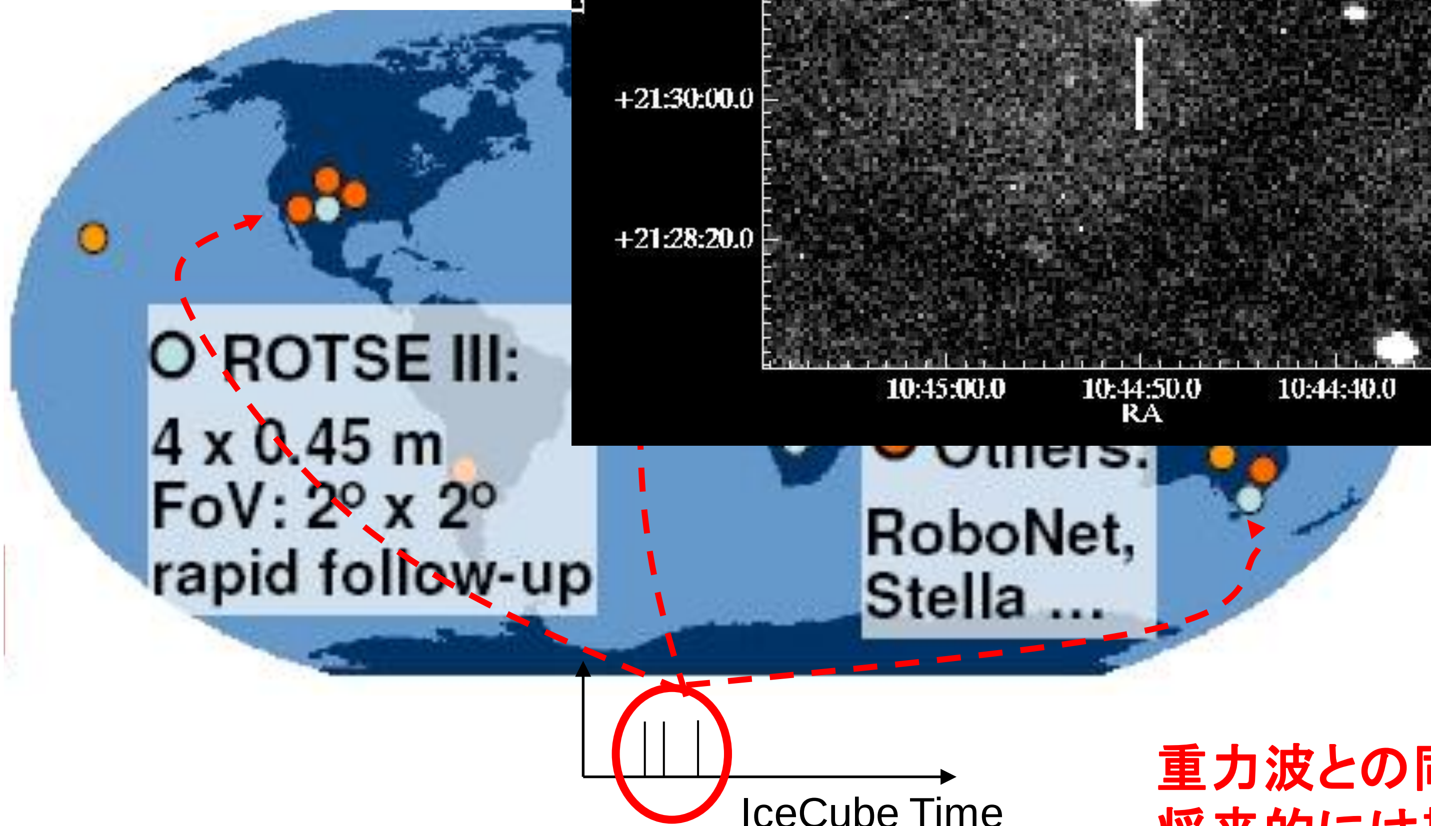
(E. Bernardini et al., astro-ph/0509396)



IceCube – ROTSE, optica

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





重力波との同時観測も
将来的には期待できる
かもしれない。

Elisa Resconi

§ Summary

まとめ

- ニュートリノはまっすぐやってくる（ソース同定に有効）。
- ニュートリノは遠くからでもやってくる（情報を失わない）。
- ニュートリノはハドロン加速の証拠となる。
- 宇宙論的ニュートリノ（Cosmogenic Neutirino）は極高エネルギー宇宙線の組成情報を与える。
- IceCubeにより、（UHECR以上に厳しい）新しい物差しが理論家に与えられだした。
- 理論家は、その新しい物差しを使ったり、理論の精密化を試みるだろう。

共に発展していきましょう。