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# Determining the neutrino flavor ratio at the astrophysical source

By G.-L. Lin

NCTU and LeCosPA

# Determination of the Neutrino Flavor Ratio at the Astrophysical Source

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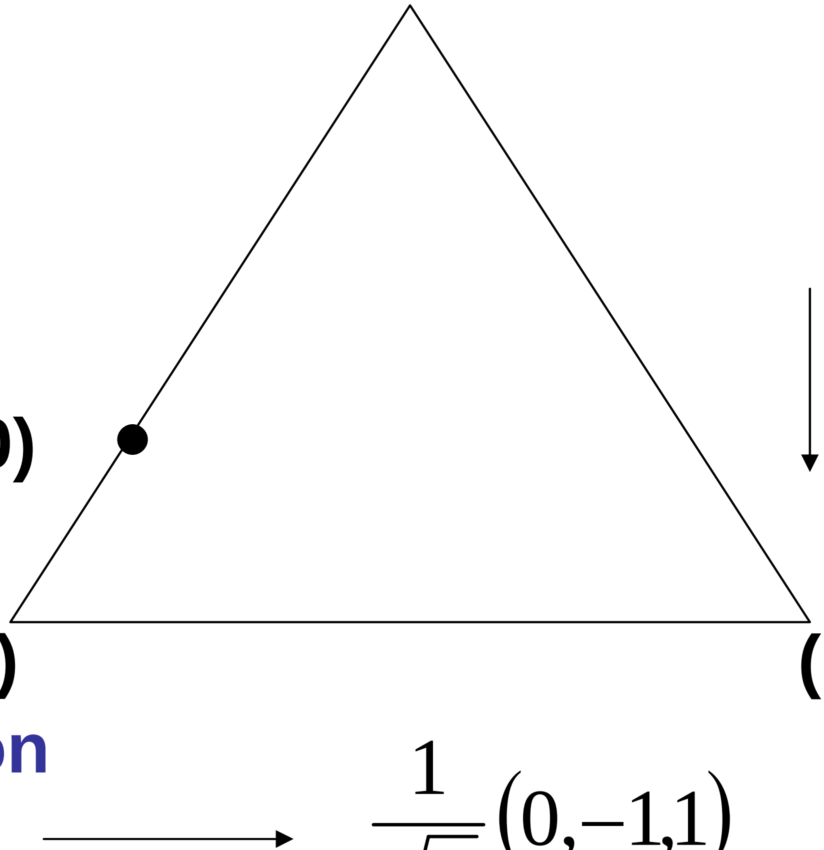
## Abstract

We discuss the reconstruction of neutrino flavor ratios at astrophysical sources from future neutrino-telescope measurements, given the knowledge of neutrino mixing angles obtained from terrestrial experiments. With a statistical analysis, we demonstrate that the pion source and the muon damped source can be distinguished at the $3\sigma$ level provided the accuracies on measuring $R \equiv \phi(\nu_\mu)/(\phi(\nu_e)+\phi(\nu_\tau))$ and $S \equiv \phi(\nu_e)/\phi(\nu_\tau)$ can both reach about 10%. On the other hand, the above two sources are very difficult to distinguish by merely measuring $R$ alone. We also discuss the effect of leptonic CP phase on such a flavor-ratio reconstruction.

PACS numbers: 95.85.Ry, 14.60.Pq, 95.55.Vj



**β source**

**(1,0,0)**

**Pion source**

**(1/3,2/3,0)**

$$\frac{1}{\sqrt{6}}\left(-2,1,1\right)$$

**(0,1,0)**

**(0,0,1)**

**Damped muon source**

$$\frac{1}{\sqrt{2}}\left(0,-1,1\right)$$

$$\Phi_0=\left(\phi_0\left(\nu_e\right),\phi_0\left(\nu_\mu\right),\phi_0\left(\nu_\tau\right)\right)$$

$$\phi_0\left(\nu_e\right)+\phi_0\left(\nu_\mu\right)+\phi_0\left(\nu_\tau\right)=1$$

# The β source (1,0,0)

**Motivated by the correlation of the arrival direction of the cosmic rays to the Galactic Plane (GP) near EeV ($10^{18}$ eV) energies**

**AGASA 1998; Fly's Eye 1998**

**Directional signal requires relatively-stable neutral primaries.**

**Neutron decay length is about 10 kpc for $E_n$=1 EeV. Smaller energy neutrons can decay**

$$n \rightarrow p + e^- + \overline{\nu}_e$$

**L. A. Anchordoqui, H. Goldberg, F. Halzen and T. J. Weiler, 2004**

# Pion source (1/3,2/3,0)

$$\pi^+ \to \mu^+ + \nu_\mu$$

$$\mu^+ \to \bar{\nu}_\mu + e^+ + \nu_e$$

**Energies of various neutrinos are comparable, i.e., muon decays before losing its energy by interactions.**

**Cosmogenic (GZK) neutrinos produced by** $p + \gamma_{CMB} \to \Delta^+ \to n + \pi^+$ **and the subsequent pion decay fit into this category.**

# Damped muon source (0,1,0)

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\mu^+ \rightarrow \overline{\nu}_\mu + e^+ + \nu_e$$

**Muon loses significant amount of energy before it decays:**

**(1) muon interacts with matter**

**J. P. Rachen and P. Meszaros, 1998**

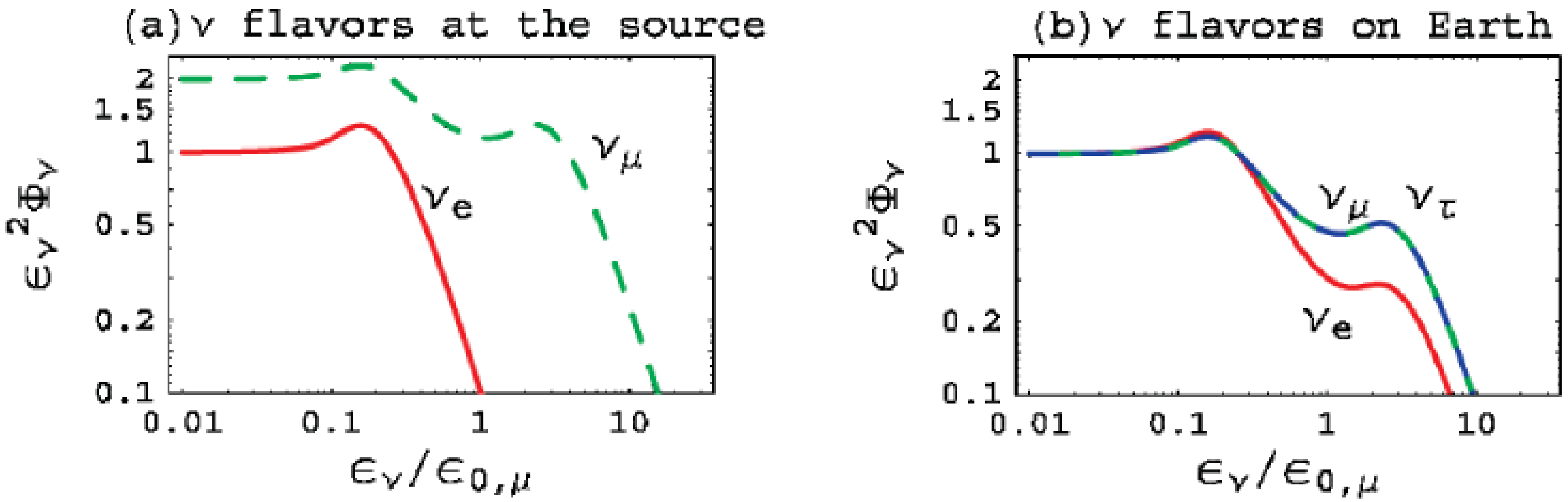
**(2) Muon interacts with background photon field**

**M. Kacherliess, O. Ostapchenko and R. Tomas, arXiv: 0708.3007**

**See also**

**T. Kashti and E. Waxman Phy. Rev. Lett. 2005**

**Neutrinos from muon decays are out of the spectrum**



**T. Kashti and E. Waxman Phy. Rev. Lett. 2005**

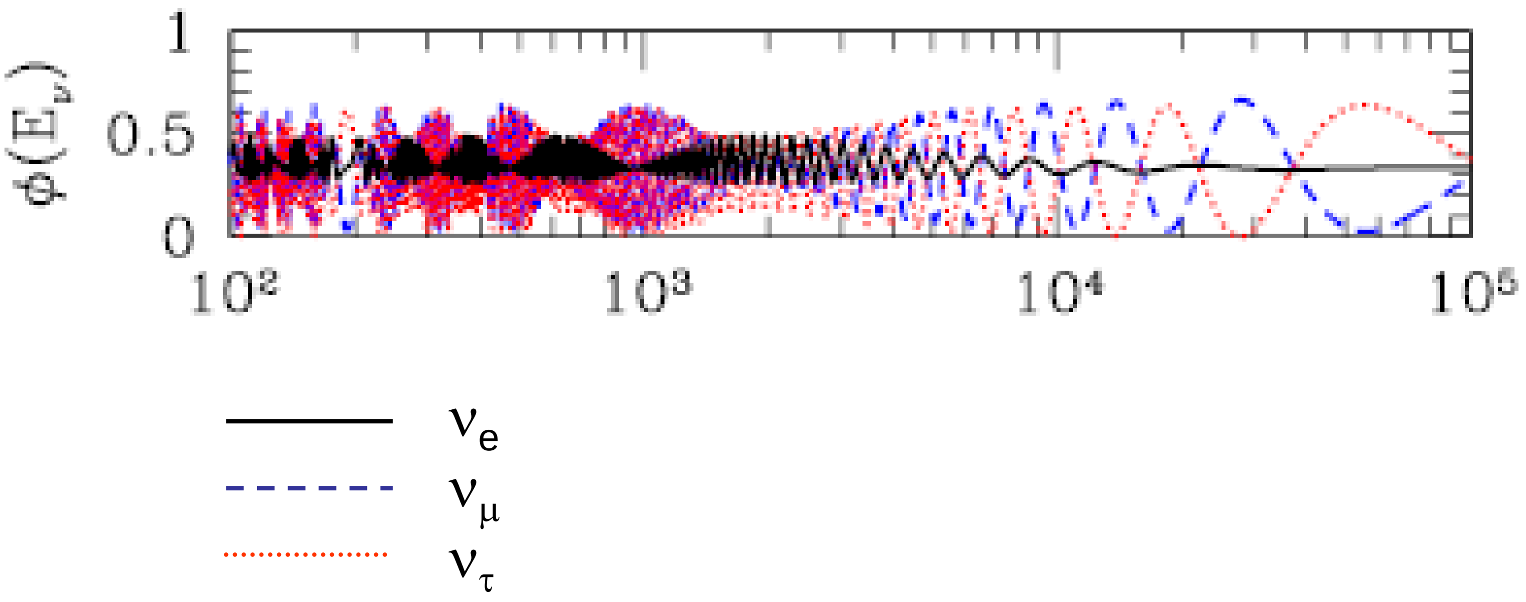
Transition from pion source to muon-damped source

# Source with a significant tau neutrino flux

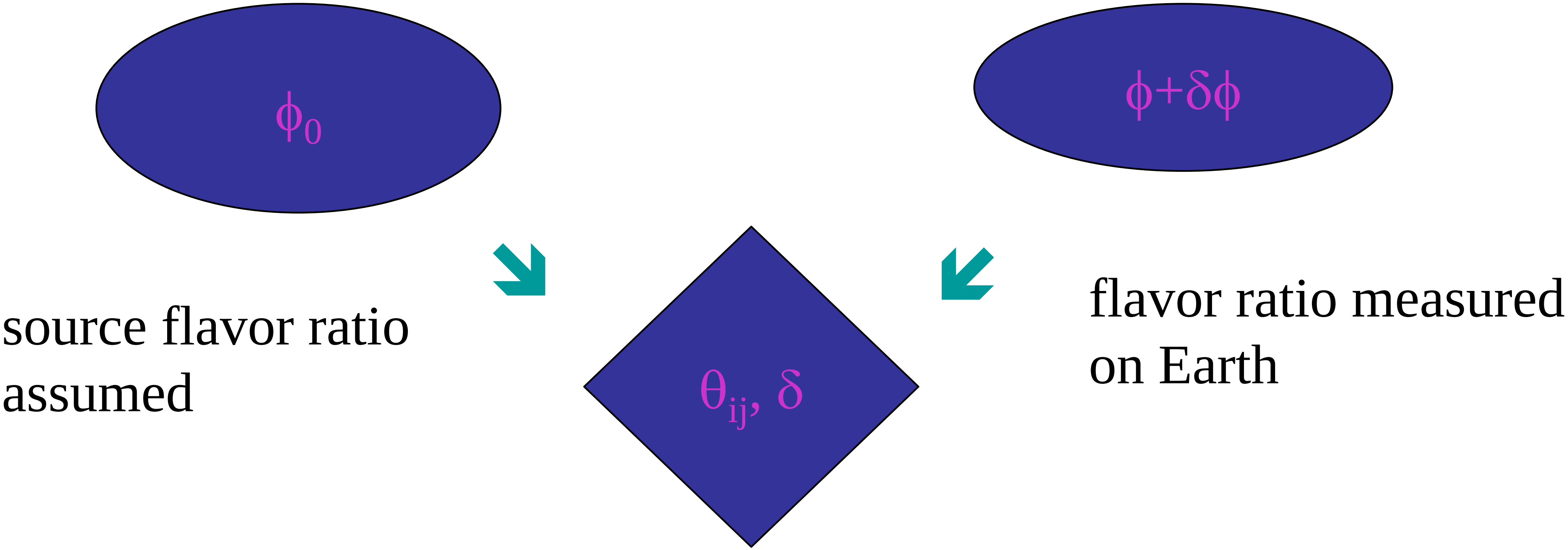
**Optically thick sources: highly relativistic GRB jets**

**Neutrinos already oscillate inside the object.**

**O. Mena, I. Mocioiu and S. Razzaque, 2006**



# The usual approach



$\phi_0$

$\phi+\delta\phi$

source flavor ratio assumed

flavor ratio measured on Earth

$\theta_{ij}$, $\delta$

Probe neutrino mixing parameters

S. Pakvasa, Mod. Phys. Lett. A **19**, 1163 (2004) [Yad. Fiz. **67**, 1179 (2004)].

M. L. Costantini and F. Vissani, Astropart. Phys. **23**, 477 (2005); F. Vissani, Astropart. Phys. **26**, 310 (2006); astro-ph/0609575.

P. Bhattacharjee and N. Gupta, arXiv:hep-ph/0501191.

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P. D. Serpico, Phys. Rev. D **73**, 047301 (2006).

Z. Z. Xing and S. Zhou, Phys. Rev. D **74**, 013010 (2006).

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W. Rodejohann, JCAP **0701**, 029 (2007).

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K. Blum, Y. Nir and E. Waxman, arXiv:0706.2070 [hep-ph].

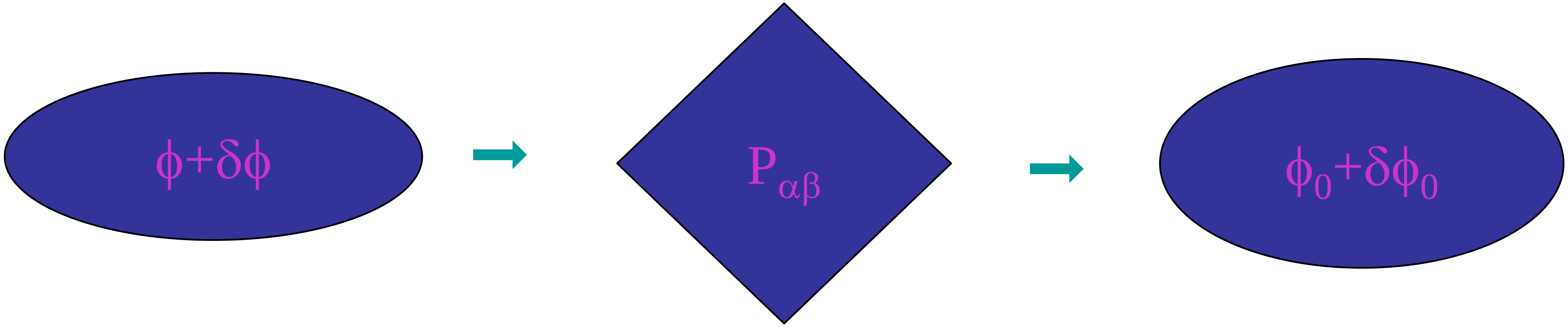
G. R. Hwang and S. Kim, Phys. Rev. D **78**, 093008 (2008).

S. Pakvasa, W. Rodejohann and T. J. Weiler, JHEP **0802**, 005 (2008).

S. Choubey, V. Niro and W. Rodejohann, Phys. Rev. D **77**, 113006 (2008).

M. Maltoni and W. Winter, JHEP **0807**, 064 (2008).

# Our approach



$\phi+\delta\phi$ → $P_{\alpha\beta}$ → $\phi_0+\delta\phi_0$

flavor ratio
measured on Earth

Oscillation matrix
depending on $\theta_{ij}$, $\delta$

source flavor ratio
deduced
with certain accuracy

# Reconstructing the source flavor ratio

$$\left(\phi(\nu_e),\phi(\nu_\mu),\phi(\nu_\tau)\right)=\left(\phi_0(\nu_e),\phi_0(\nu_\mu),\phi_0(\nu_\tau)\right)\begin{pmatrix}P_{ee}&P_{e\mu}&P_{e\tau}\\P_{\mu e}&P_{\mu\mu}&P_{\mu\tau}\\P_{\tau e}&P_{\tau\mu}&P_{\tau\tau}\end{pmatrix}$$

Measured flux

**P**

$$P_{\alpha\beta}\equiv P\left(\nu_\alpha\rightarrow\nu_\beta\right)=\sum_{i=1}^{3}\left|U_{\alpha i}\right|^2\left|U_{\beta i}\right|^2,\ \text{where}\ \nu_\alpha=U_{\alpha i}\nu_i$$

Flavor Eigenstate

Mass Eigenstate

***$U_{\alpha i}$*** contains 3 mixing angles--$\theta_{12}$, $\theta_{23}$, and $\theta_{13}$
one CP phase $\delta_{CP}$

$$\begin{aligned}
P_{ee} &= \left(1-\frac{1}{2}\omega\right)(1-D^2)^2+D^4,\\
P_{e\mu} &= \frac{1}{4}(1-D^2)\left[\omega(1+\Delta)+(4-\omega)(1-\Delta)D^2+2\sqrt{\omega(1-\omega)(1-\Delta^2)}D\cos\delta\right],\\
P_{e\tau} &= \frac{1}{4}(1-D^2)\left[\omega(1-\Delta)+(4-\omega)(1+\Delta)D^2-2\sqrt{\omega(1-\omega)(1-\Delta^2)}D\cos\delta\right],\\
P_{\mu\mu} &= \frac{1}{2}\left[(1+\Delta^2)-(1-\Delta)^2D^2(1-D^2)\right]\\
&- \frac{1}{8}\omega\left[(1+\Delta)^2+(1-\Delta)^2D^4-(1-\Delta^2)D^2(2+4\cos^2\delta)\right]\\
&- \frac{1}{2}\sqrt{\omega(1-\omega)(1-\Delta^2)}\left[(1+\Delta)-(1-\Delta)D^2\right]D\cos\delta,\\
P_{\mu\tau} &= \frac{1}{2}(1-\Delta^2)(1-D^2+D^4)\\
&- \frac{1}{8}\omega\left[(1-\Delta^2)(1+4D^2\cos^2\delta+D^4)-2(1+\Delta^2)D^2\right]\\
&+ \frac{1}{2}\sqrt{\omega(1-\omega)(1-\Delta^2)}\Delta(1+D^2)D\cos\delta,\\
P_{\tau\tau} &= \frac{1}{2}\left[(1+\Delta^2)-(1+\Delta)^2D^2(1-D^2)\right]\\
&- \frac{1}{8}\omega\left[(1-\Delta)^2+(1+\Delta)^2D^4-(1-\Delta^2)D^2(2+4\cos^2\delta)\right]\\
&+ \frac{1}{2}\sqrt{\omega(1-\omega)(1-\Delta^2)}\left[(1-\Delta)-(1+\Delta)D^2\right]D\cos\delta,
\end{aligned}\tag{A1}$$

$$\omega\equiv\sin^2 2\theta_{12},\ \Delta\equiv\cos 2\theta_{23},\ D\equiv\sin\theta_{13}$$

$\delta$ CP phase

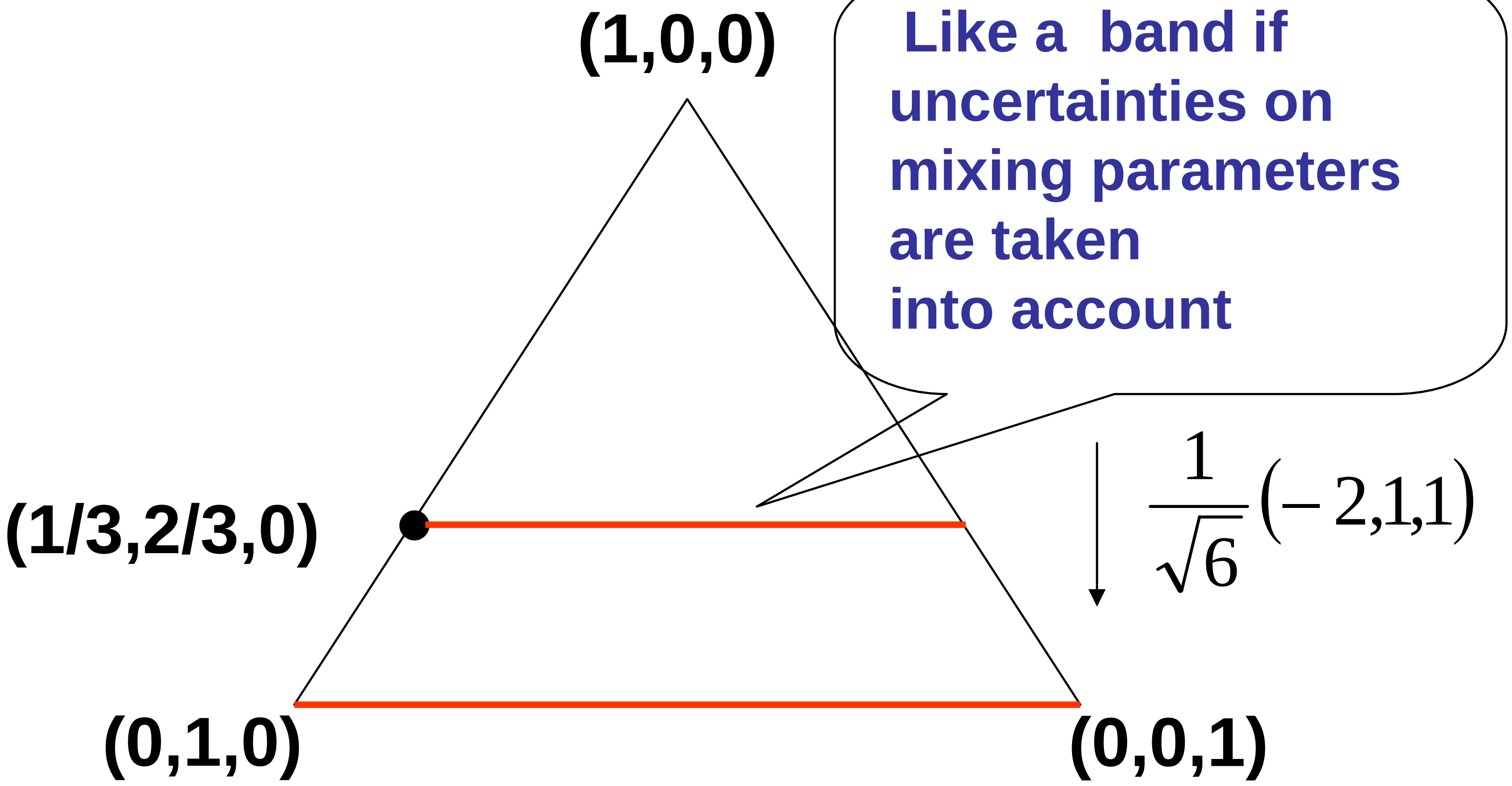
$\theta_{23}=45°$, $\theta_{13}=0°$

$$P=\frac{1}{8}\begin{pmatrix} 8-4\omega & 2\omega & 2\omega \\ 2\omega & 4-\omega & 4-\omega \\ 2\omega & 4-\omega & 4-\omega \end{pmatrix},$$

where $\omega=\sin^2 2\theta_{12}$

This matrix is singular!

# Uncertainties: mixing parameter and measurements



**Like a band if uncertainties on mixing parameters are taken into account**

$$\downarrow \quad \frac{1}{\sqrt{6}}(-2,1,1)$$

Degeneracy direction: $\phi_0(\nu_\mu)+\phi_0(\nu_\tau)$=constant

$$\longrightarrow \quad \frac{1}{\sqrt{2}}(0,-1,1)$$

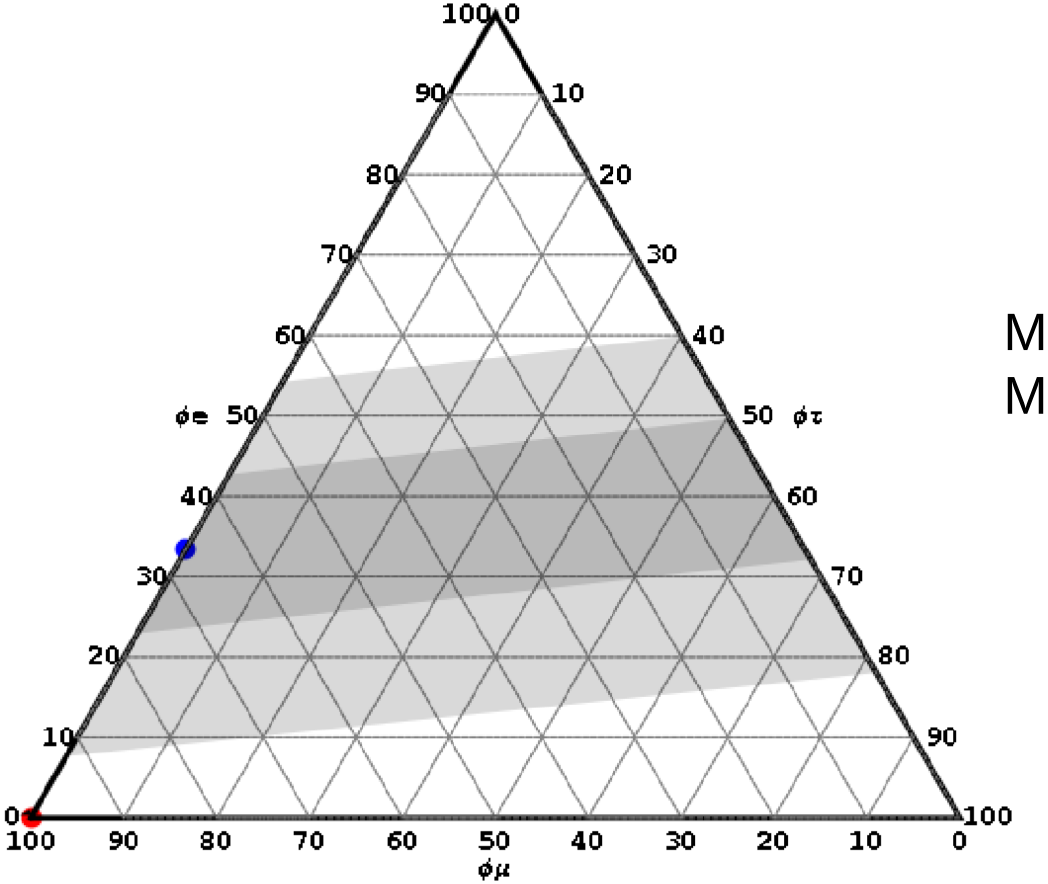
# ν flavor astronomy require a large number of events

## Pion Source

Require statistical error ~10%
So ~100 events needed.

$$\sin^2\theta_{12} = 0.32^{+0.02}_{-0.02},$$
$$\sin^2\theta_{23} = 0.45^{+0.09}_{-0.06},$$
$$\sin^2\theta_{13} < 0.019\ (90\%\ \mathrm{C.L.})$$
$$\delta_{\mathrm{CP}} = 0$$

M.C. Gonzalez-Garcia and
M. Maltoni, Phys. Rept. 2008

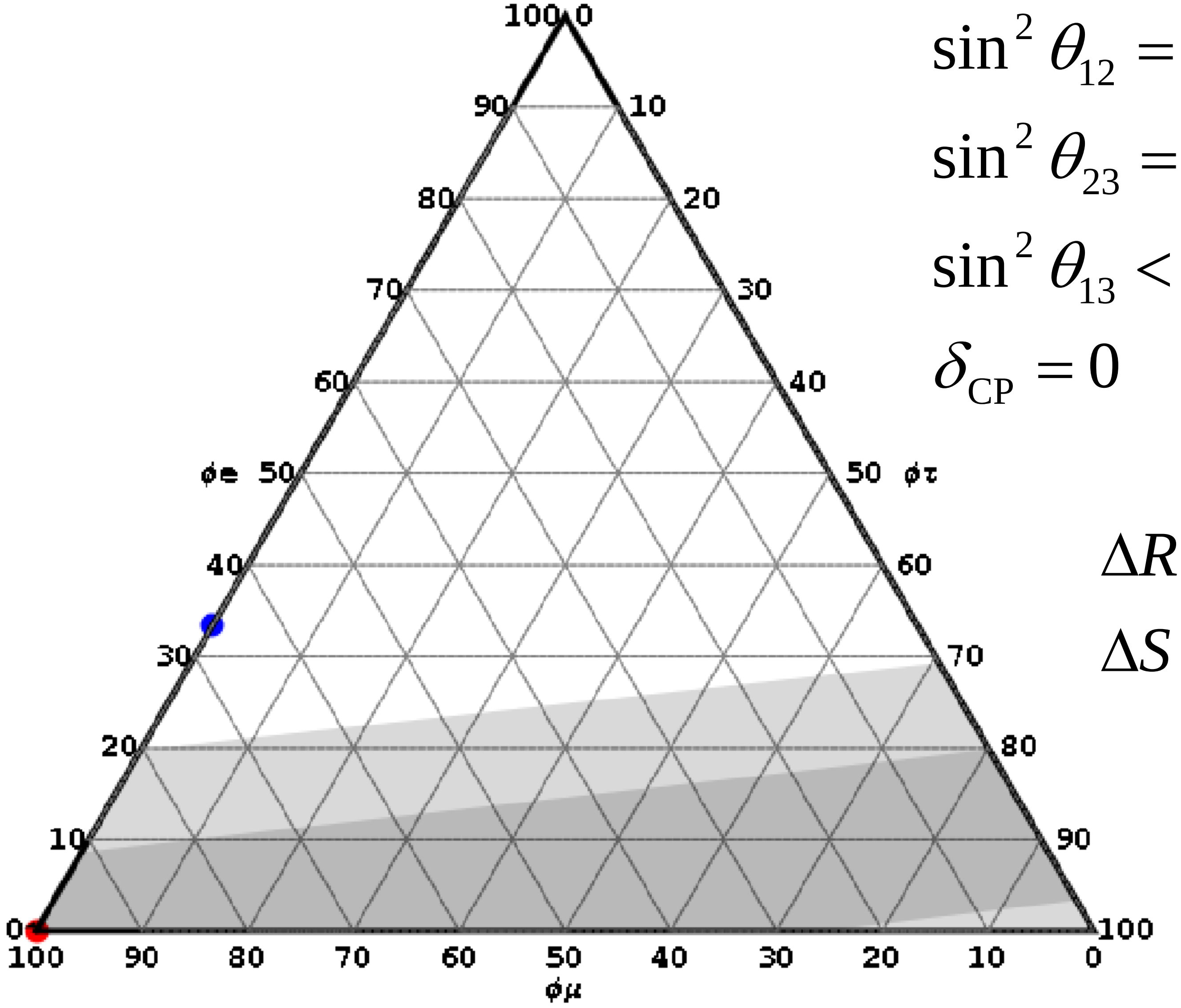


$$R \equiv \phi(\nu_\mu)/\left(\phi(\nu_e)+\phi(\nu_\tau)\right)$$
$$S \equiv \phi(\nu_e)/\phi(\nu_\tau)$$

$$\Delta R/R = 10\%$$

$$\Delta S/S = 1.2\Delta R/R$$

# Damped Muon Source



$$\sin^2\theta_{12} = 0.32^{+0.02}_{-0.02},$$

$$\sin^2\theta_{23} = 0.45^{+0.09}_{-0.06},$$

$$\sin^2\theta_{13} < 0.019\,(90\%\ \mathrm{C.L.})$$

$$\delta_{\mathrm{CP}} = 0$$

$$\Delta R / R = 10\%$$

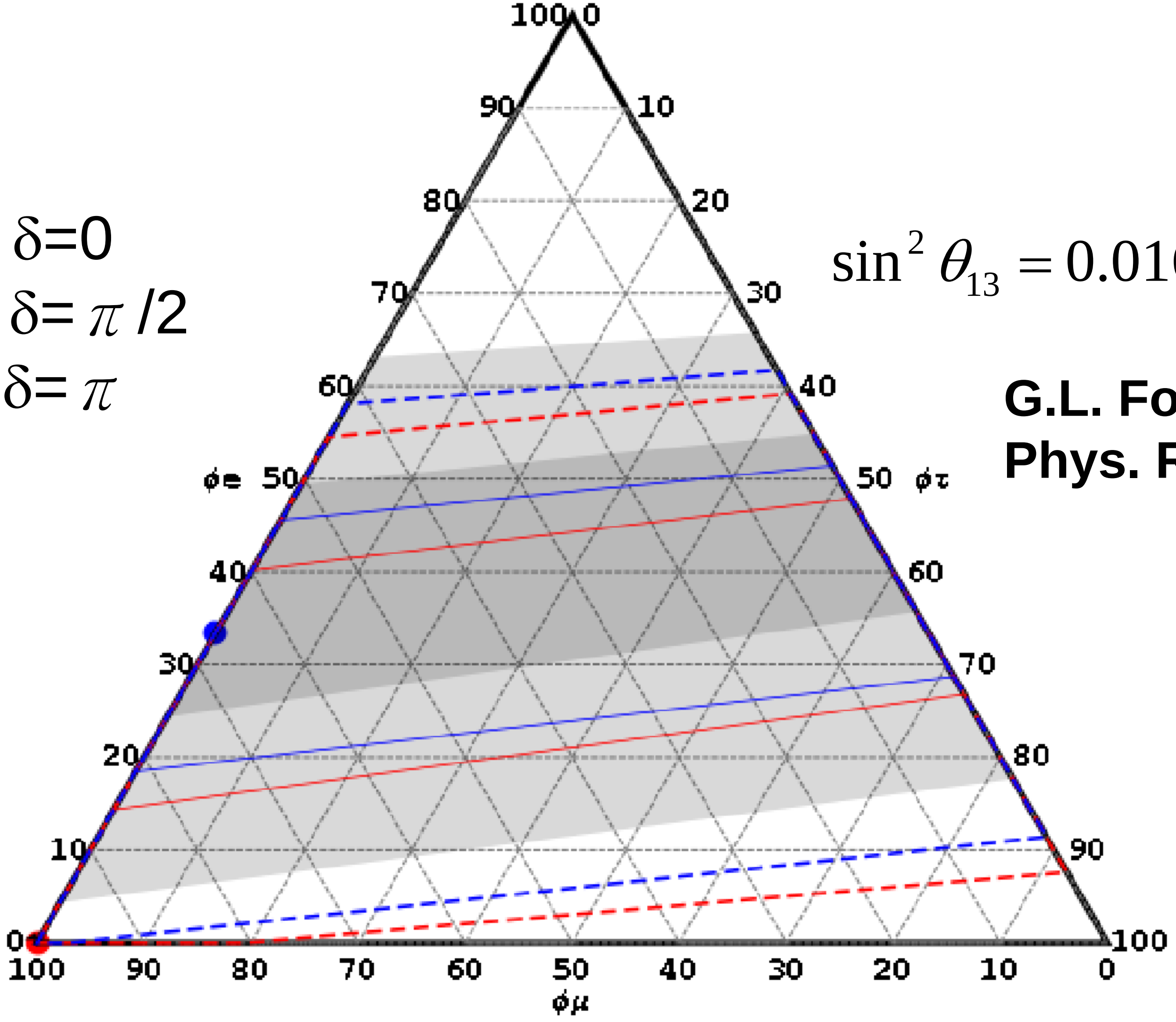
$$\Delta S / S = 1.3 \Delta R / R$$

# Pion Source

Gray: δ=0

Red: δ= $\pi$ /2

Blue: δ= $\pi$



$$\sin^2\theta_{13} = 0.016 \pm 0.010 (1\sigma)$$

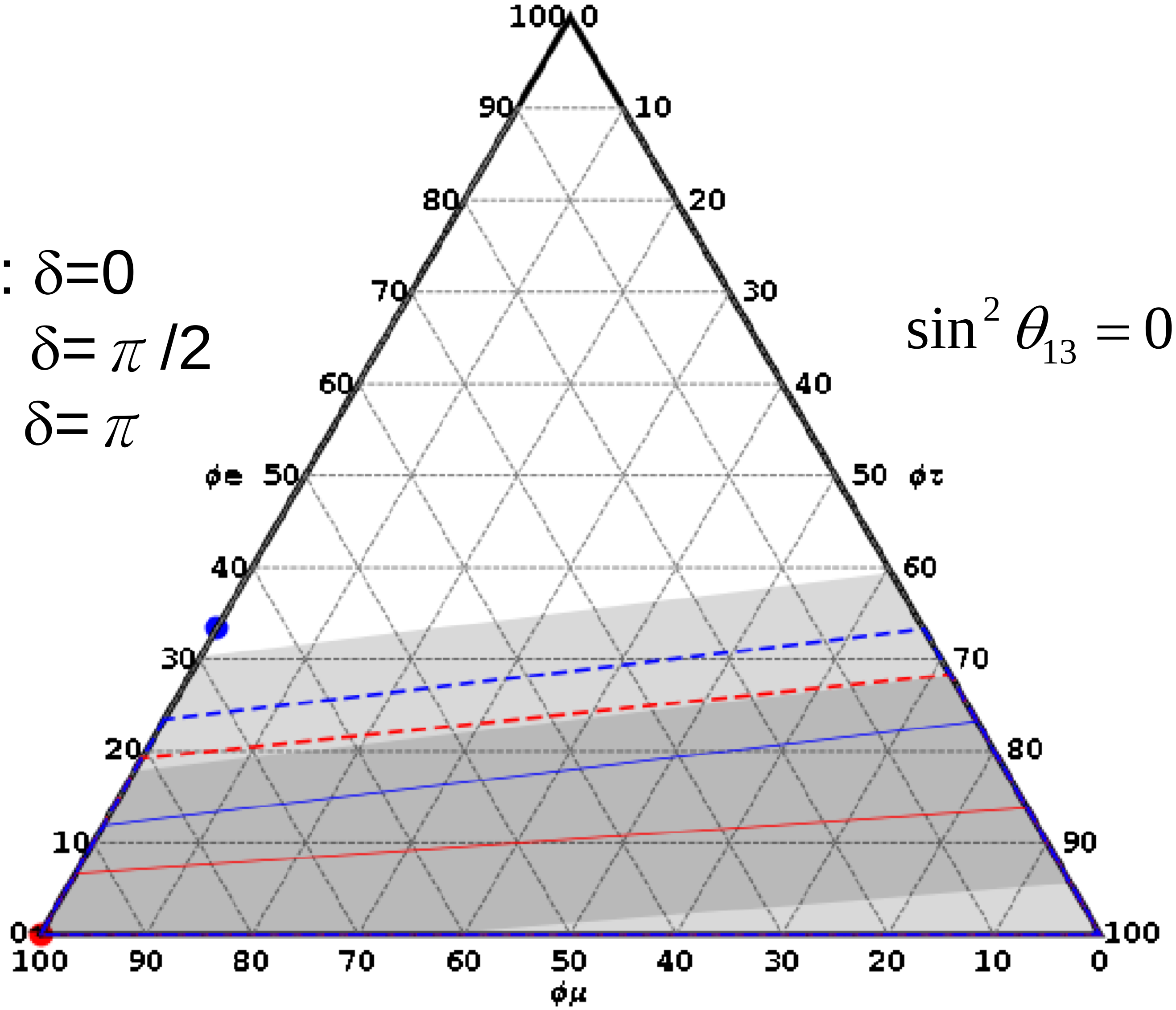
**G.L. Fogli et al., Phys. Rev. Lett. 2008**

# Damped muon source

Gray: δ=0

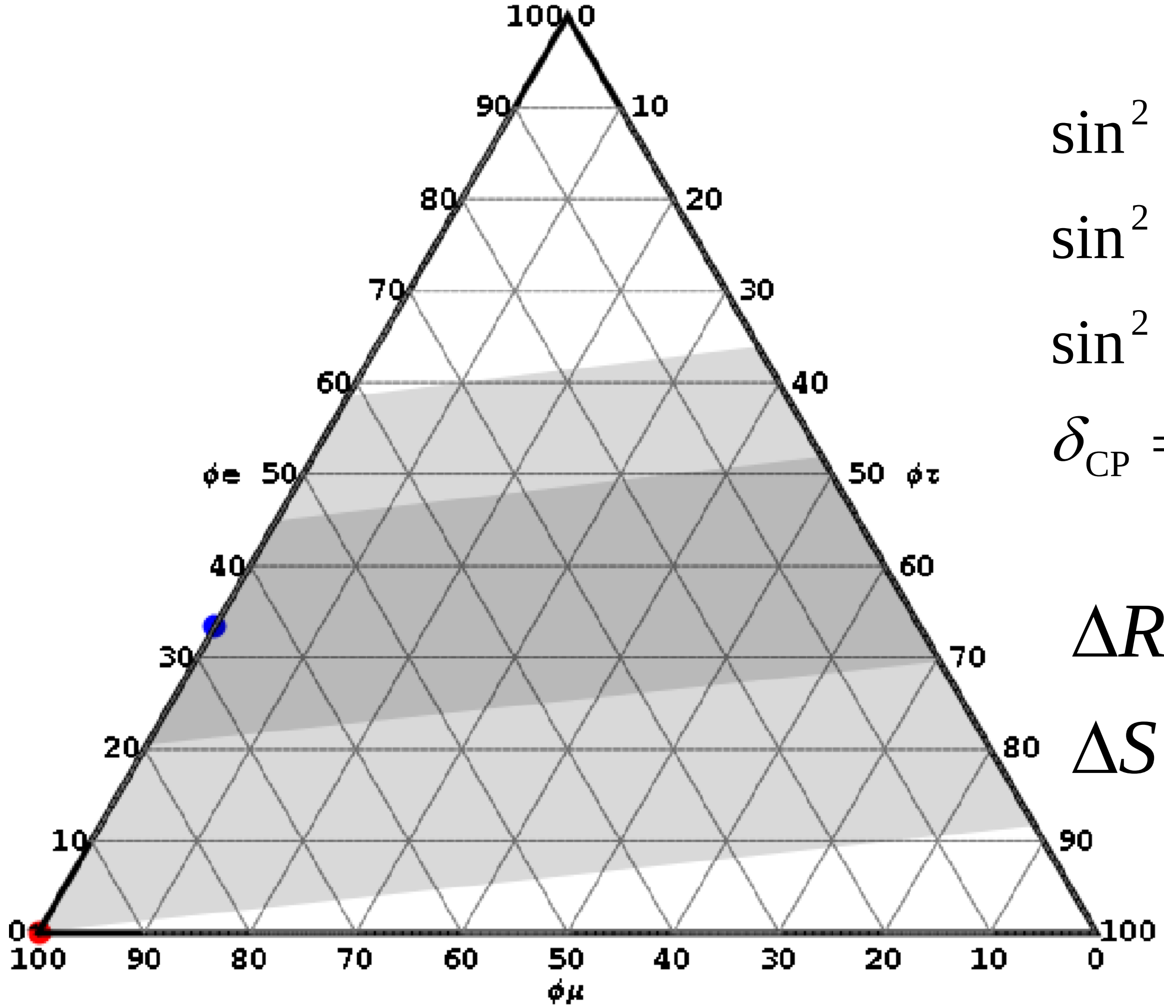
Red: δ= $\pi$ /2

Blue: δ= $\pi$



$$\sin^2\theta_{13} = 0.016 \pm 0.010 (1\sigma)$$

# Critical measurement accuracy for ruling out damped muon source



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$$\sin^2\theta_{23} = 0.45^{+0.09}_{-0.06},$$

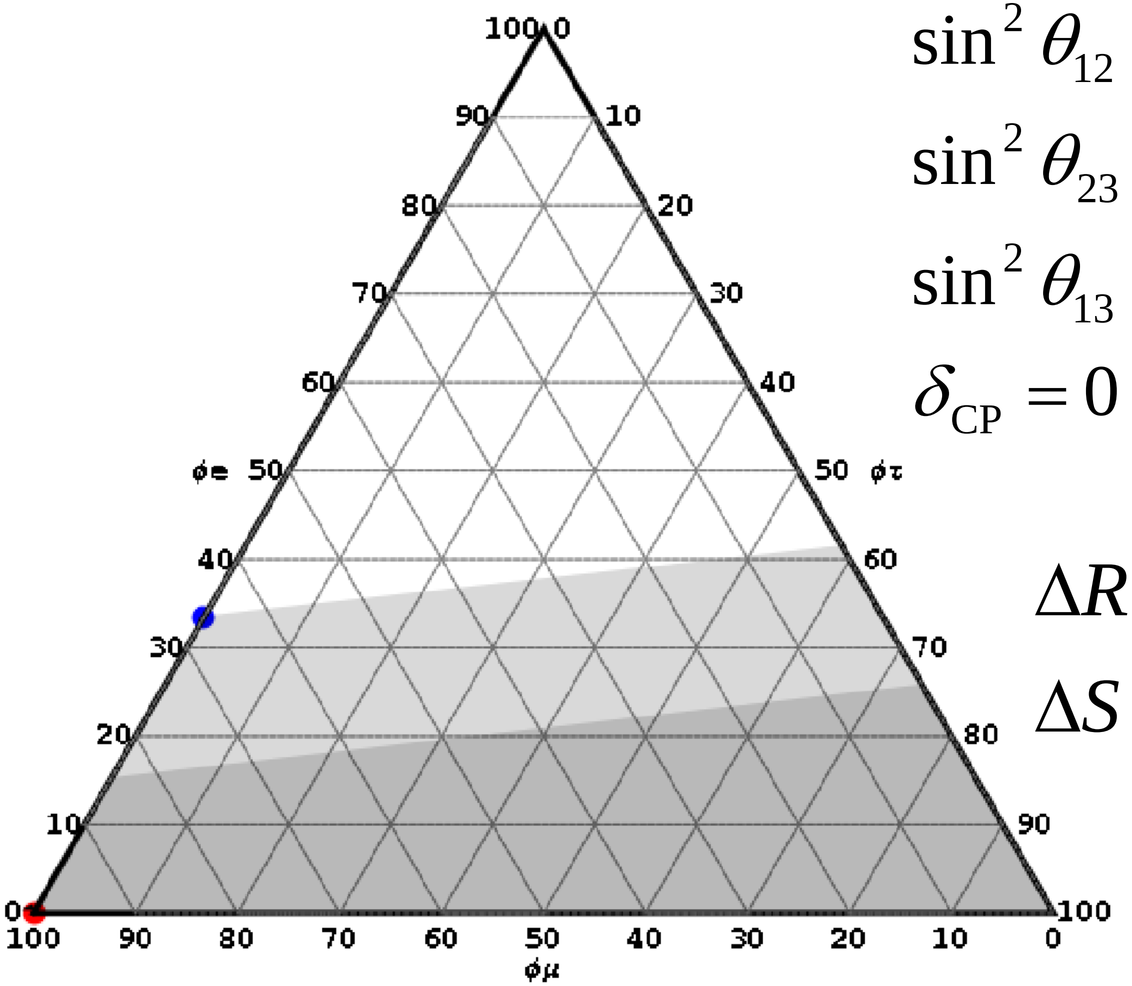
$$\sin^2\theta_{13} < 0.019\,(90\%\ \mathrm{C.L.})$$

$$\delta_{\mathrm{CP}} = 0$$

$$\Delta R / R \sim 13\%$$

$$\Delta S / S = 1.2 \Delta R / R$$

# Critical measurement accuracy for ruling out pion source



$$\sin^2\theta_{12} = 0.32^{+0.02}_{-0.02},$$

$$\sin^2\theta_{23} = 0.45^{+0.09}_{-0.06},$$

$$\sin^2\theta_{13} < 0.019\,(90\%\ \mathrm{C.L.})$$

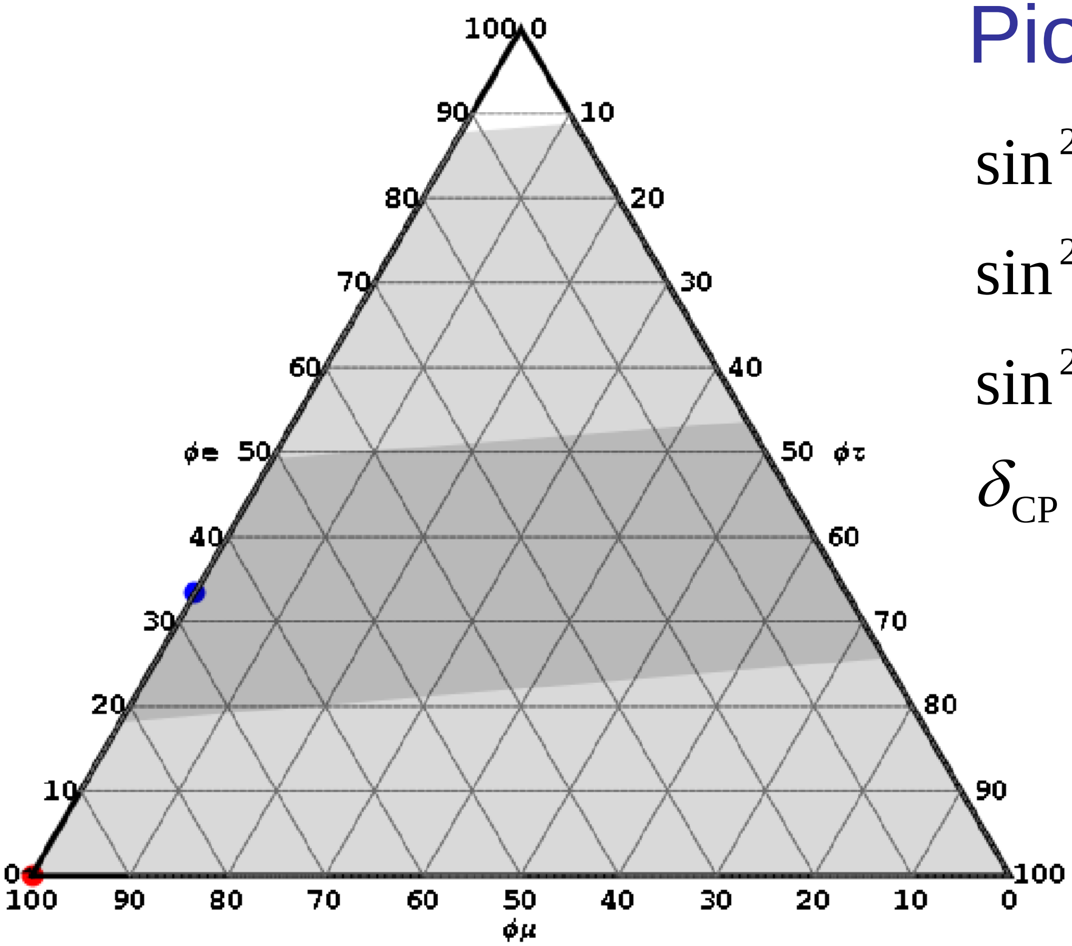
$$\delta_{\mathrm{CP}} = 0$$

$$\Delta R / R \sim 18\%$$

$$\Delta S / S = 1.3 \Delta R / R$$

# What if one only measures *R*?

It is more challenging to measure *S*
Relies on double bang signature of $\nu_\tau$



Pion source

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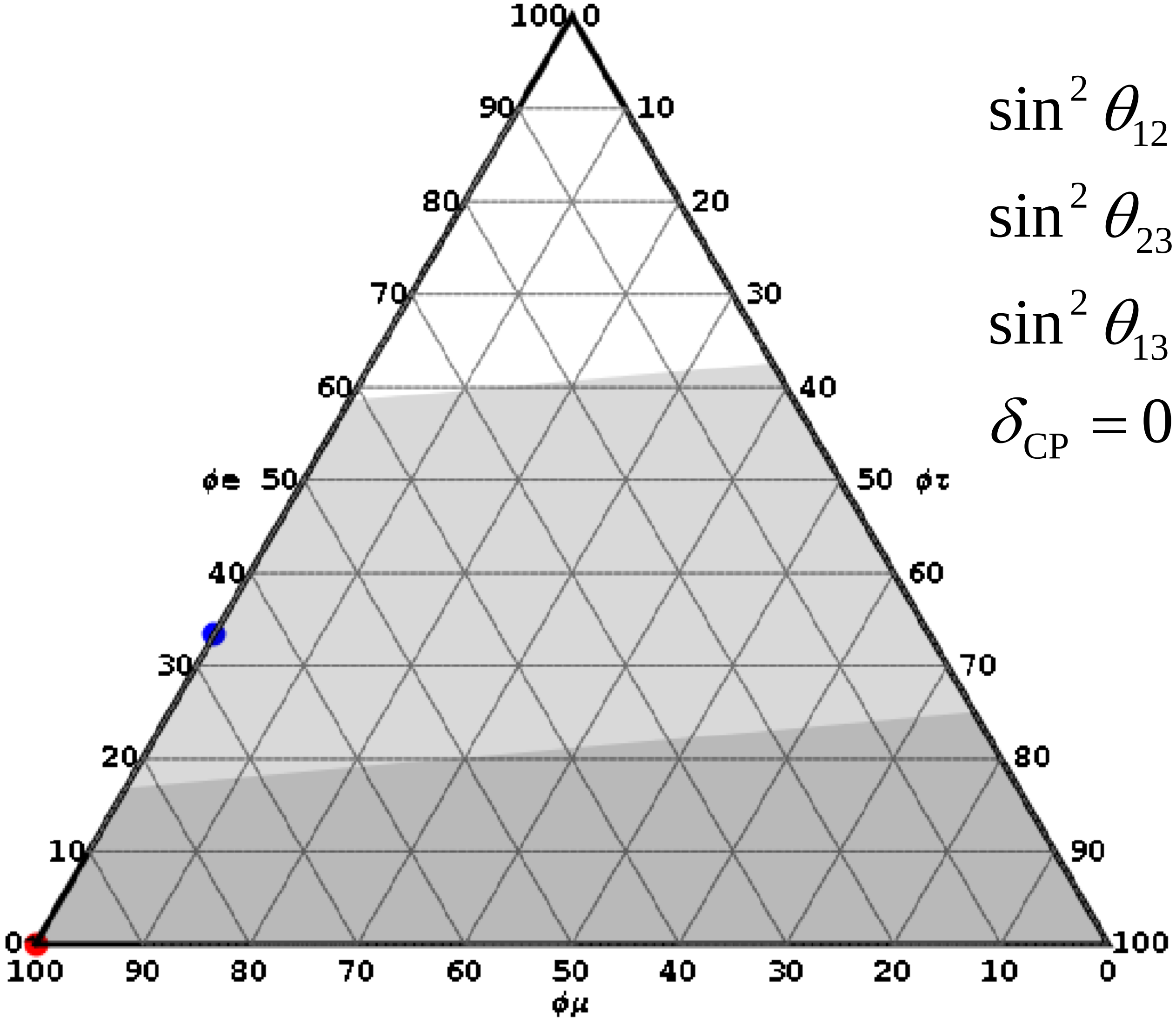
$$\sin^2\theta_{23} = 0.45^{+0.09}_{-0.06},$$

$$\sin^2\theta_{13} < 0.019\,(90\%\ \mathrm{C.L.})$$

$$\delta_{\mathrm{CP}} = 0$$

$$\Delta R / R = 10\%$$

# Damped muon source



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$$\sin^2\theta_{13} < 0.019\,(90\%\ \text{C.L.})$$

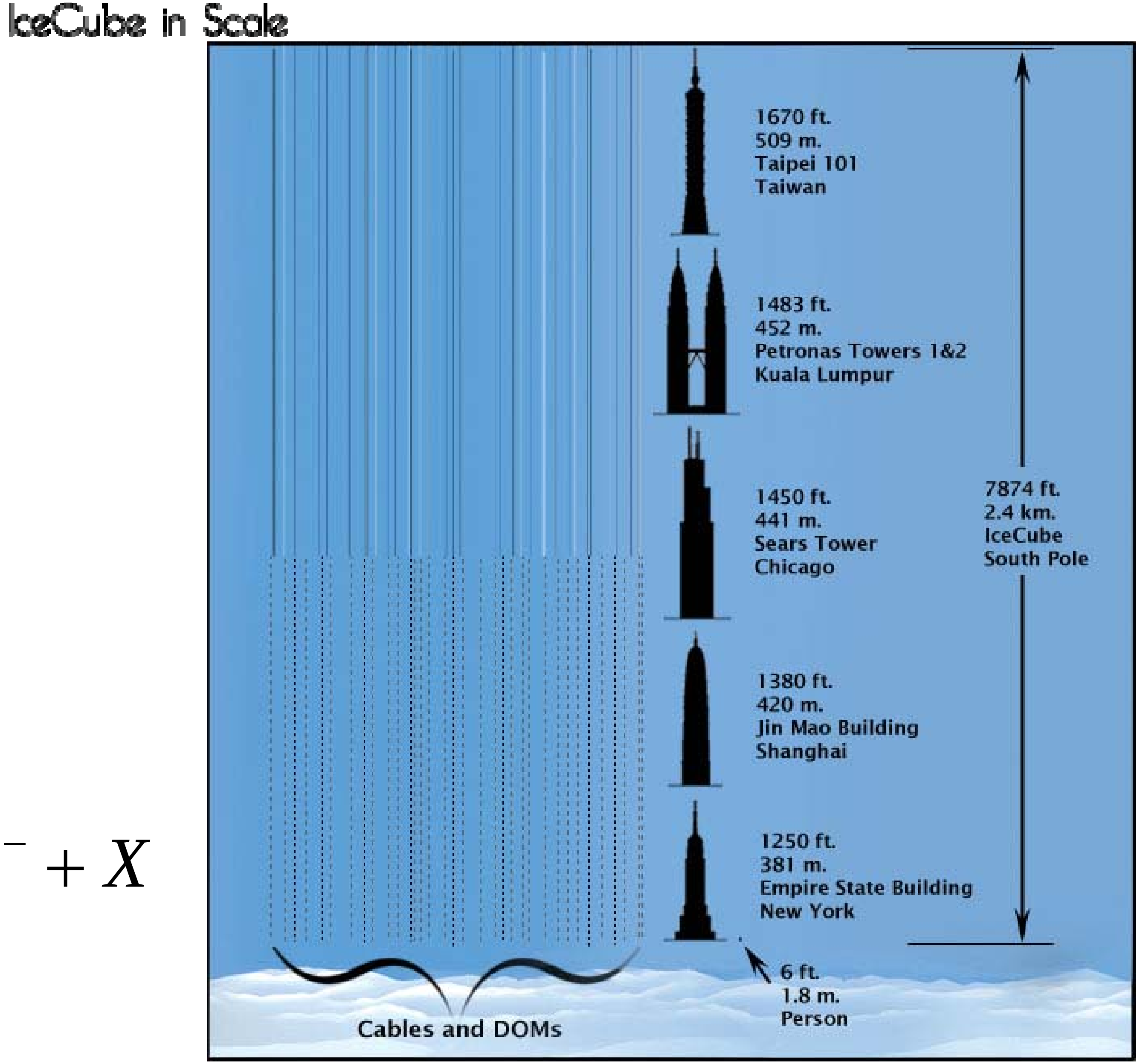
$$\delta_{\text{CP}} = 0$$

$$\Delta R / R = 10\%$$

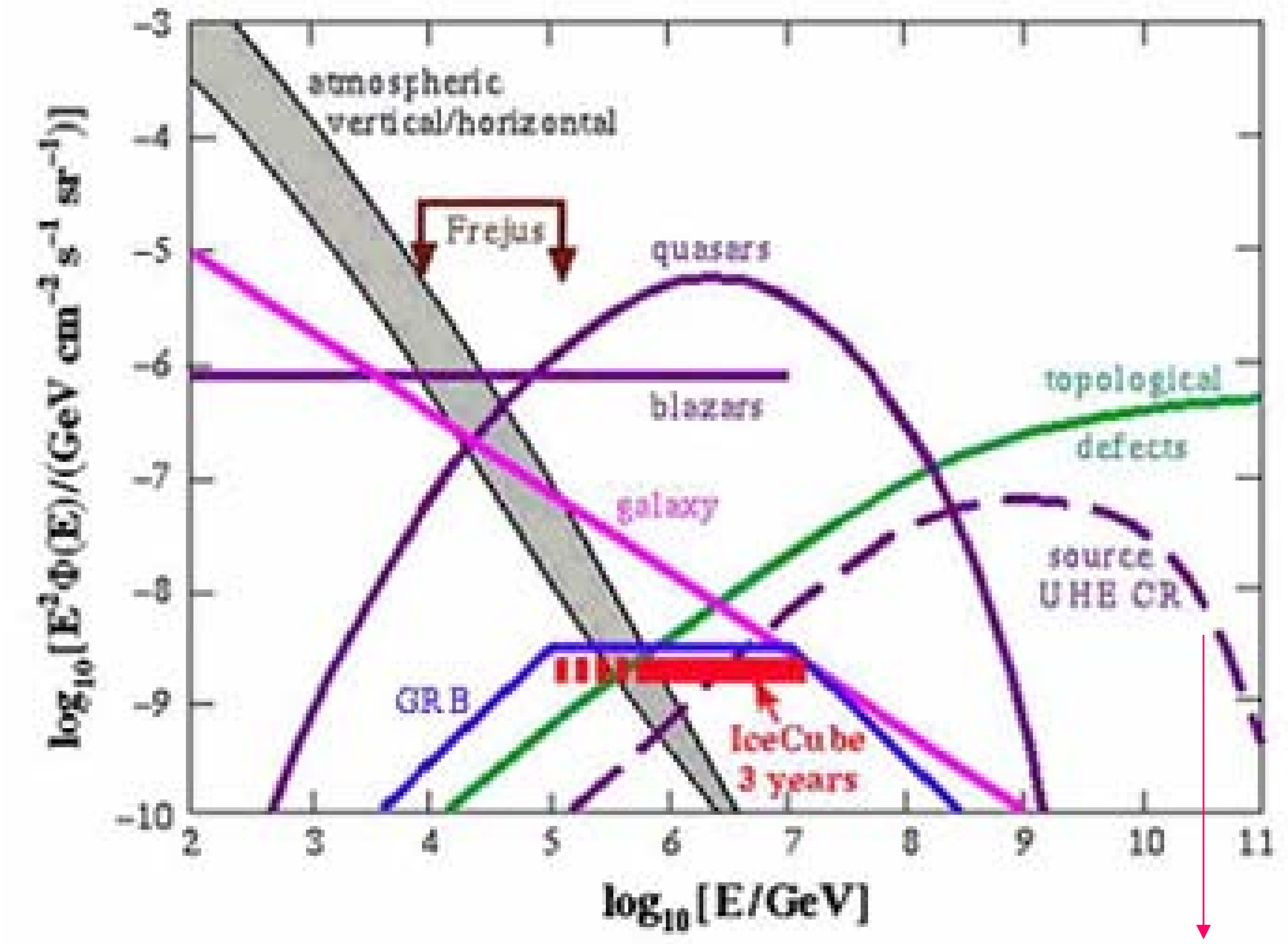
# How to detect astrophysical neutrinos？

- IceCube—PMT array in South Pole ice
- ANTARES→KM3Net—PMT array in the Mediterranean
- ANITA—Radio wave detector above South Pole
- Pierre Auger—Earth skimming tau neutrinos

$$\nu_\mu + N \rightarrow \mu^- + X$$

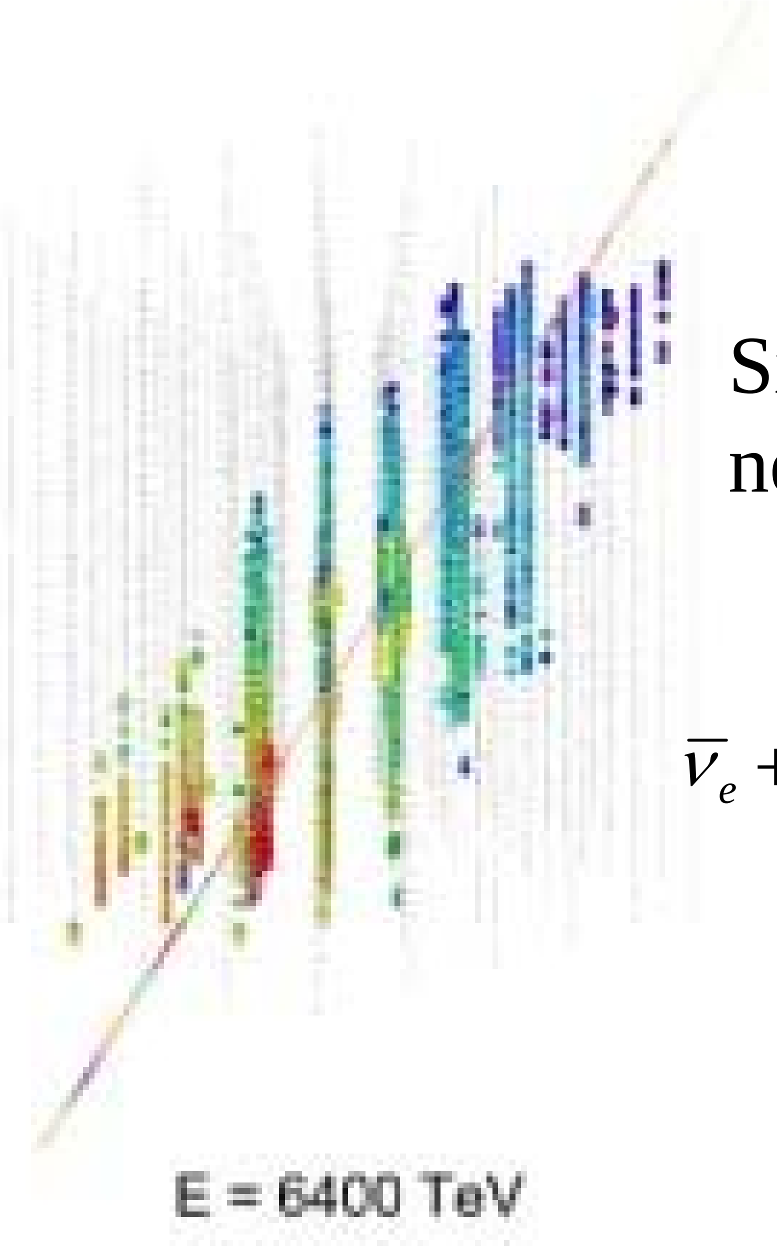


IceCube—PMT array in South Pole ice



$$\nu_\mu + N \to \mu^- + X$$

Cosmogenic neutrino flux



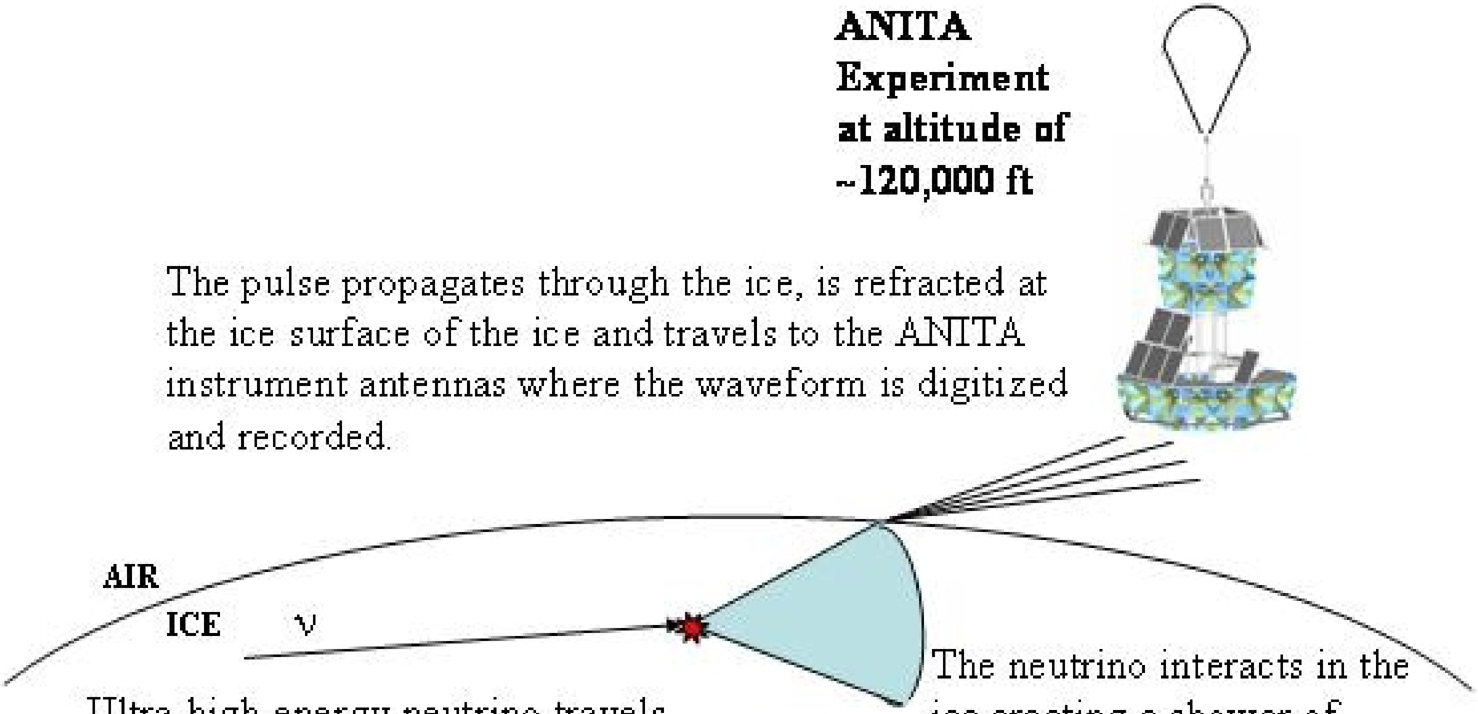
Simulated high energy neutrino event

$$\bar{\nu}_e + e^- \rightarrow W^- \rightarrow \bar{\nu}_\mu + \mu^-$$

# ANITA

## ANTARCTIC IMPULSIVE TRANSIENT ANTENNA

### A LONG DURATION BALLOON MISSION TO CONSTRAIN THE ORIGIN OF THE HIGHEST ENERGY PARTICLES IN THE UNIVERSE

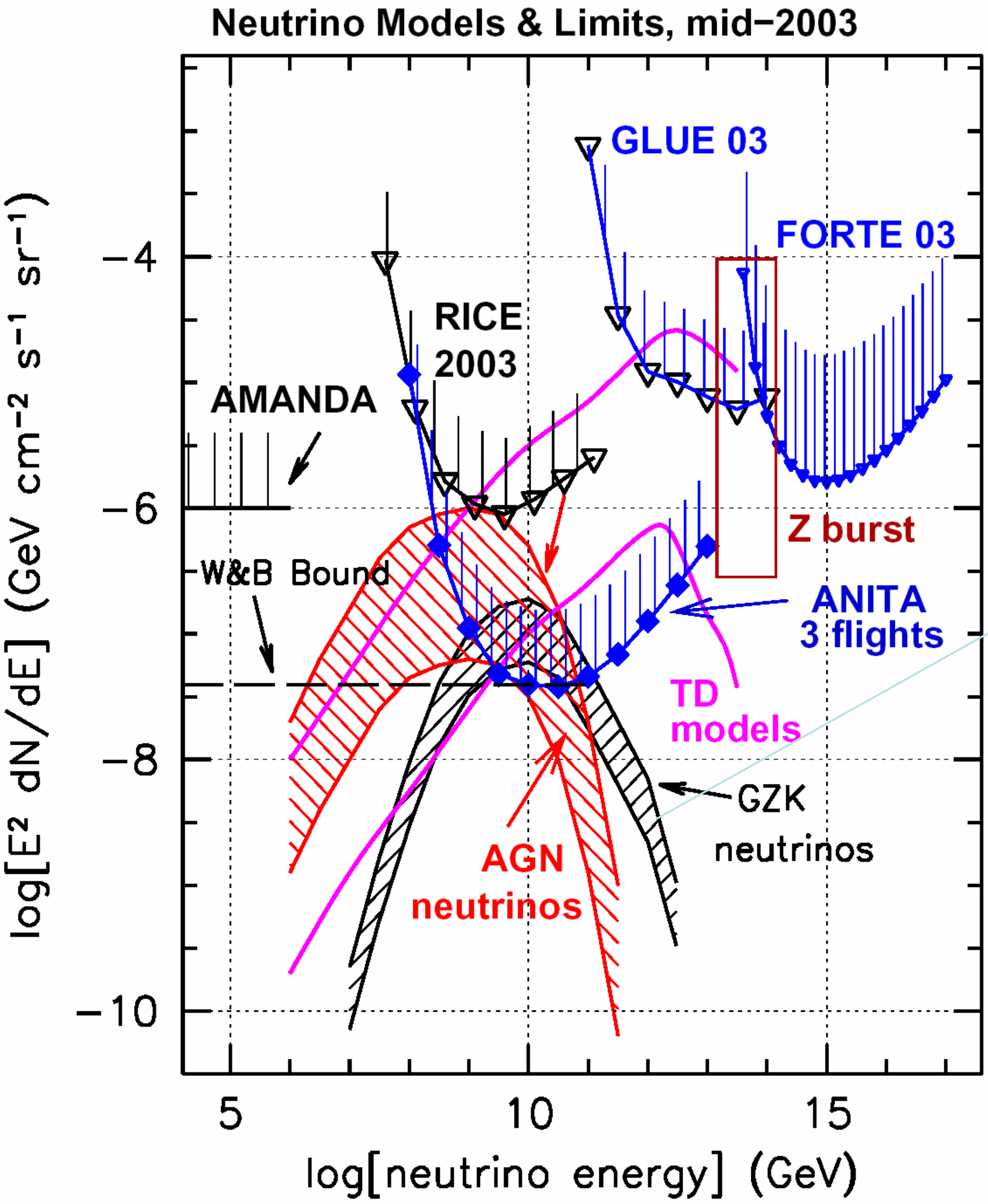


**ANITA Experiment at altitude of ~120,000 ft**

The pulse propagates through the ice, is refracted at the ice surface of the ice and travels to the ANITA instrument antennas where the waveform is digitized and recorded.

Ultra-high energy neutrino travels through the Antarctic ice.

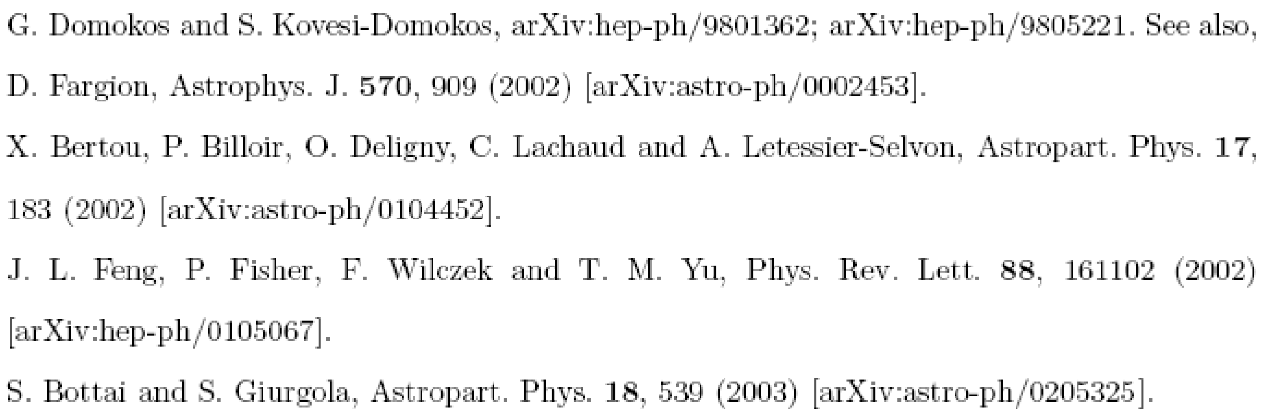
The neutrino interacts in the ice creating a shower of particles and a Cherenkov radio pulse.



Cosmogenic neutrinos

ANITA—best sensitivity near $10^{19}$ eV

Most recent launch Jan. 2009

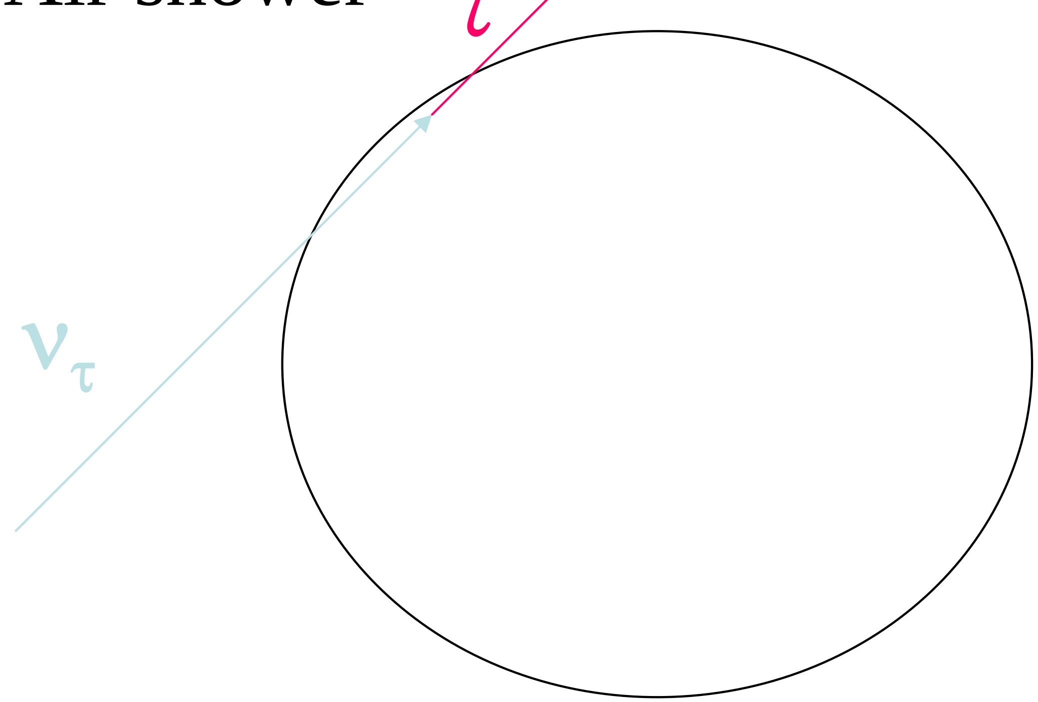


G. Domokos and S. Kovesi-Domokos, arXiv:hep-ph/9801362; arXiv:hep-ph/9805221. See also, D. Fargion, Astrophys. J. **570**, 909 (2002) [arXiv:astro-ph/0002453].

X. Bertou, P. Billoir, O. Deligny, C. Lachaud and A. Letessier-Selvon, Astropart. Phys. **17**, 183 (2002) [arXiv:astro-ph/0104452].

J. L. Feng, P. Fisher, F. Wilczek and T. M. Yu, Phys. Rev. Lett. **88**, 161102 (2002) [arXiv:hep-ph/0105067].

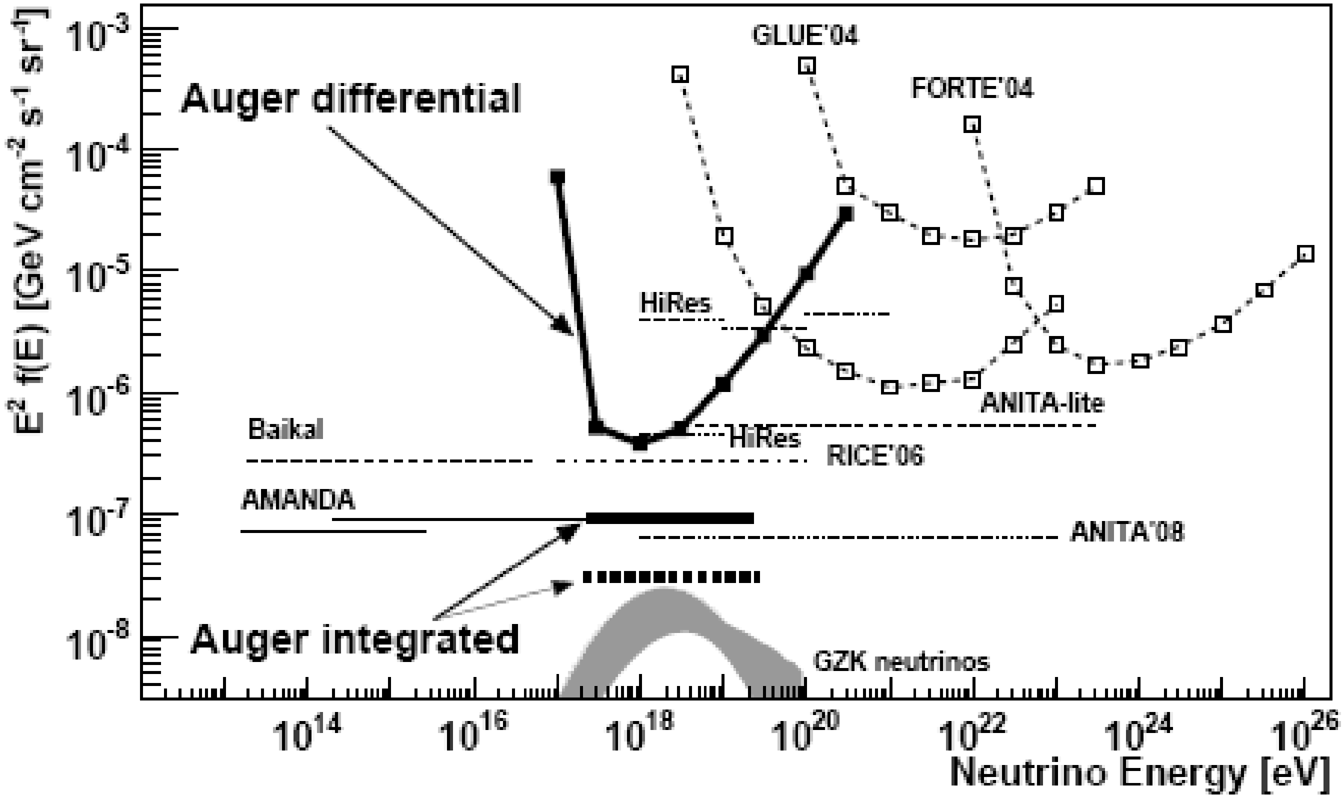
S. Bottai and S. Giurgola, Astropart. Phys. **18**, 539 (2003) [arXiv:astro-ph/0205325].



- J.-J. Tseng, T.-W. Yeh, H. Athar, M. A. Huang, F.-F. Lee and GLL, Phys. Rev. D 2003
- GLL,

# Earth-skimming tau neutrinos

# Auger result on UHE tau neutrino flux

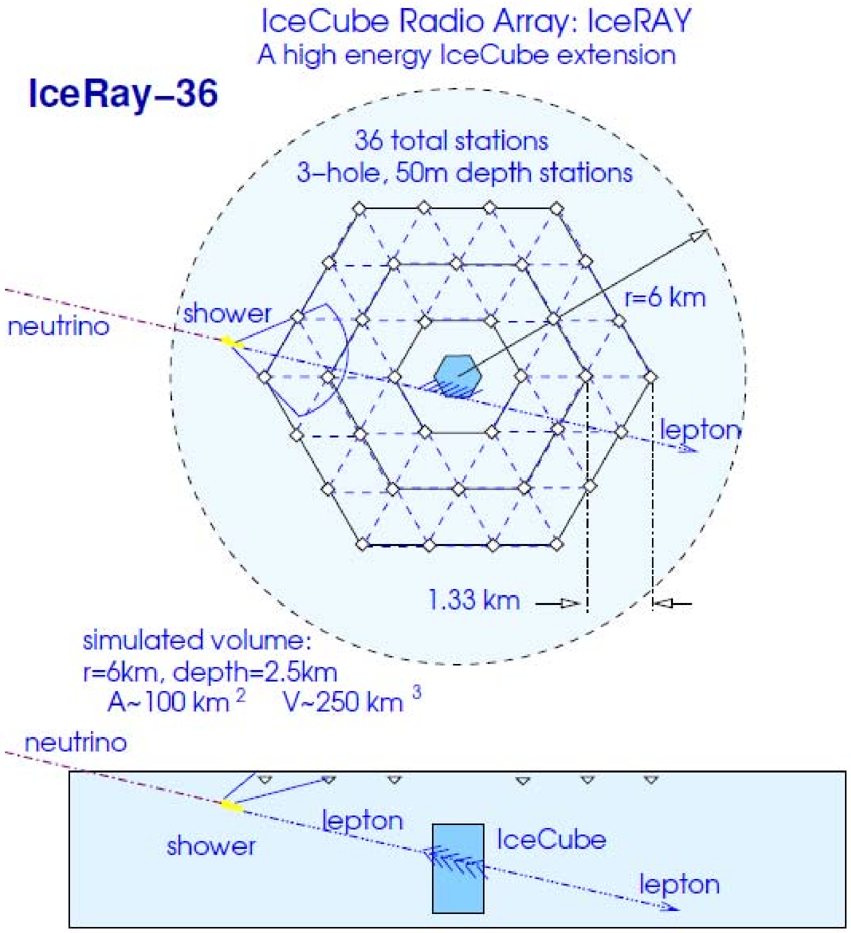


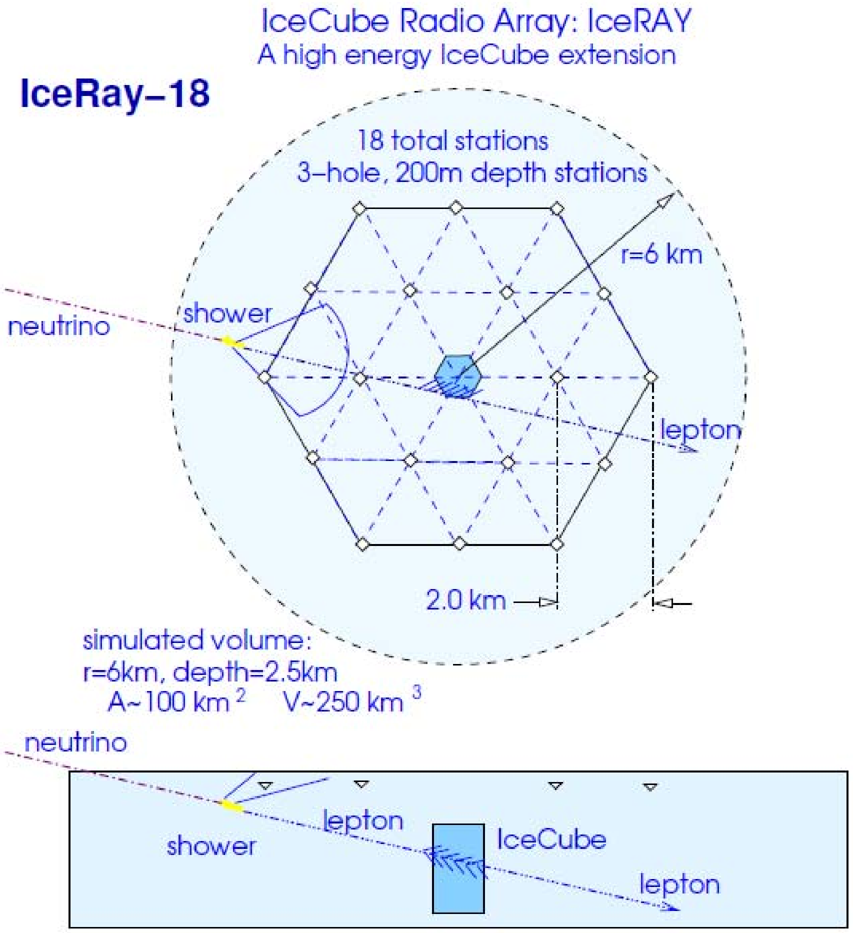
**90% C.L.**

arXiv:0903.3385 [astro-ph.HE]

# IceRay deployment-radio and water Cherenkov technique put together

**Higher density, shallow 50m** **sparse, deep 200m**





**8km**

# Summary—omitting details on how neutrino telescopes measure *R* and *S*….

- The structure of the oscillation probability matrix *P* makes it difficult to constrain $\phi_0(\nu_\mu)-\phi_0(\nu_\tau)$
- 10% accuracy in terrestrial measurements on both *R* and *S* is required for distinguishing the pion source and muon-damped source—caused by the structure of *P.*
- Taking Waxman-Bahcall upper bound $E^2\Phi_0=2\times10^{-8}$ GeV/cm$^2$ s sr, 10% accuracy ( O(100) events) takes IceCube detector more than a decade→ neutrino flavor astronomy challenging!
- Improved measurements on neutrino mixing parameters are not very helpful to the above situation. See P. 20
- To use the astrophysical source for probing the neutrino mixing parameter, it is unrealistic to assume a precise knowledge on the neutrino flavor ratio at the source.