Neutrino mixing at high energy neutrino telescopes

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CARE '05 - ECFA/BENE

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$\Delta x \Delta p_x \geq \hbar$
Theoretical Physics Division

Overview of the Talk

- *Neutrino telescopes: an overview*

- *Neutrino mixing at neutrino telescopes*

- *"Galactic β-beams" and muon-damped sources*

- *Conclusions*

Neutrino-telescopes: an overview

High-Energy ν astronomy: a new sky

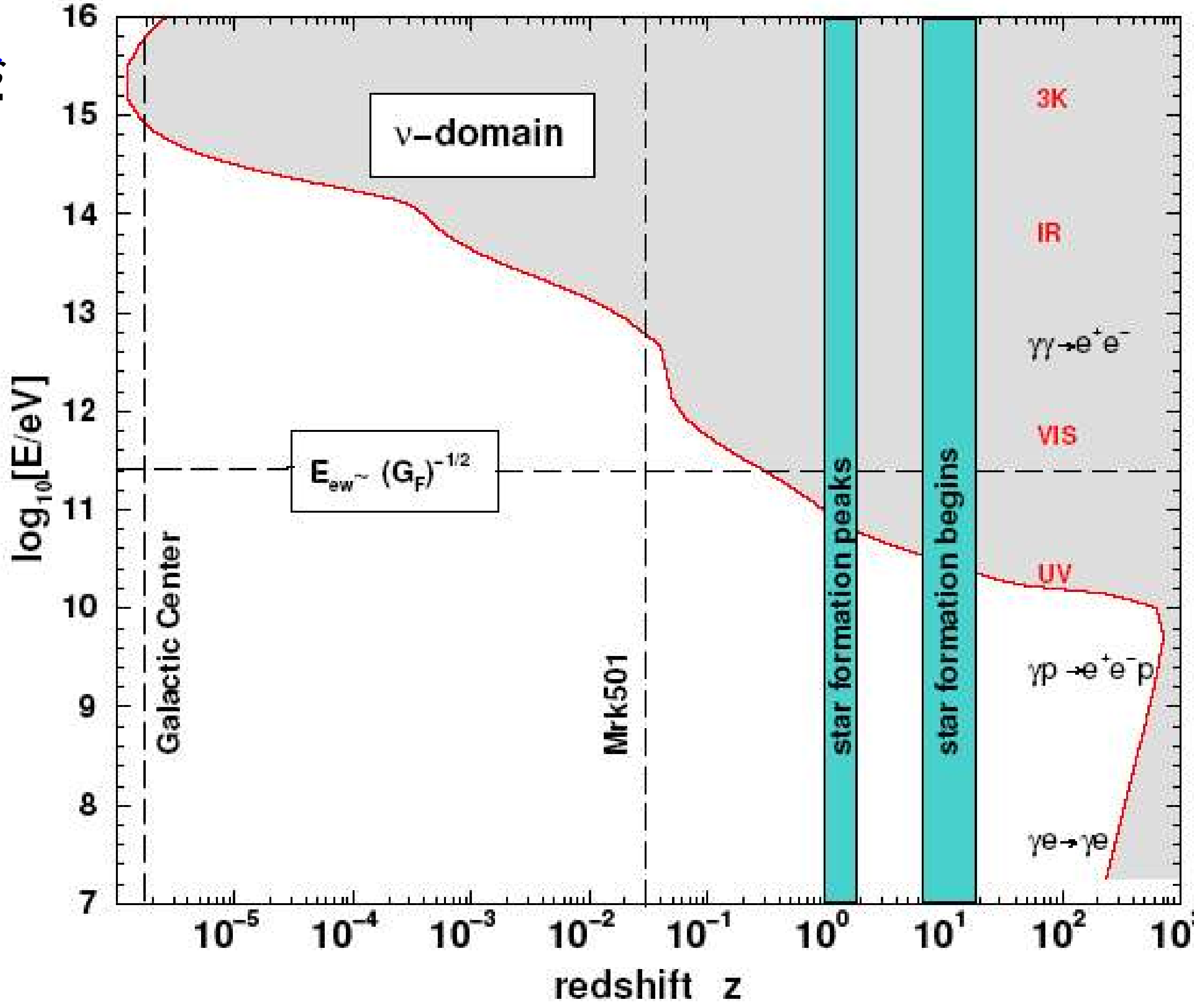
Neutrinos: a powerful tool for high energy astrophysics

+)Directional signal
(differently from CR)

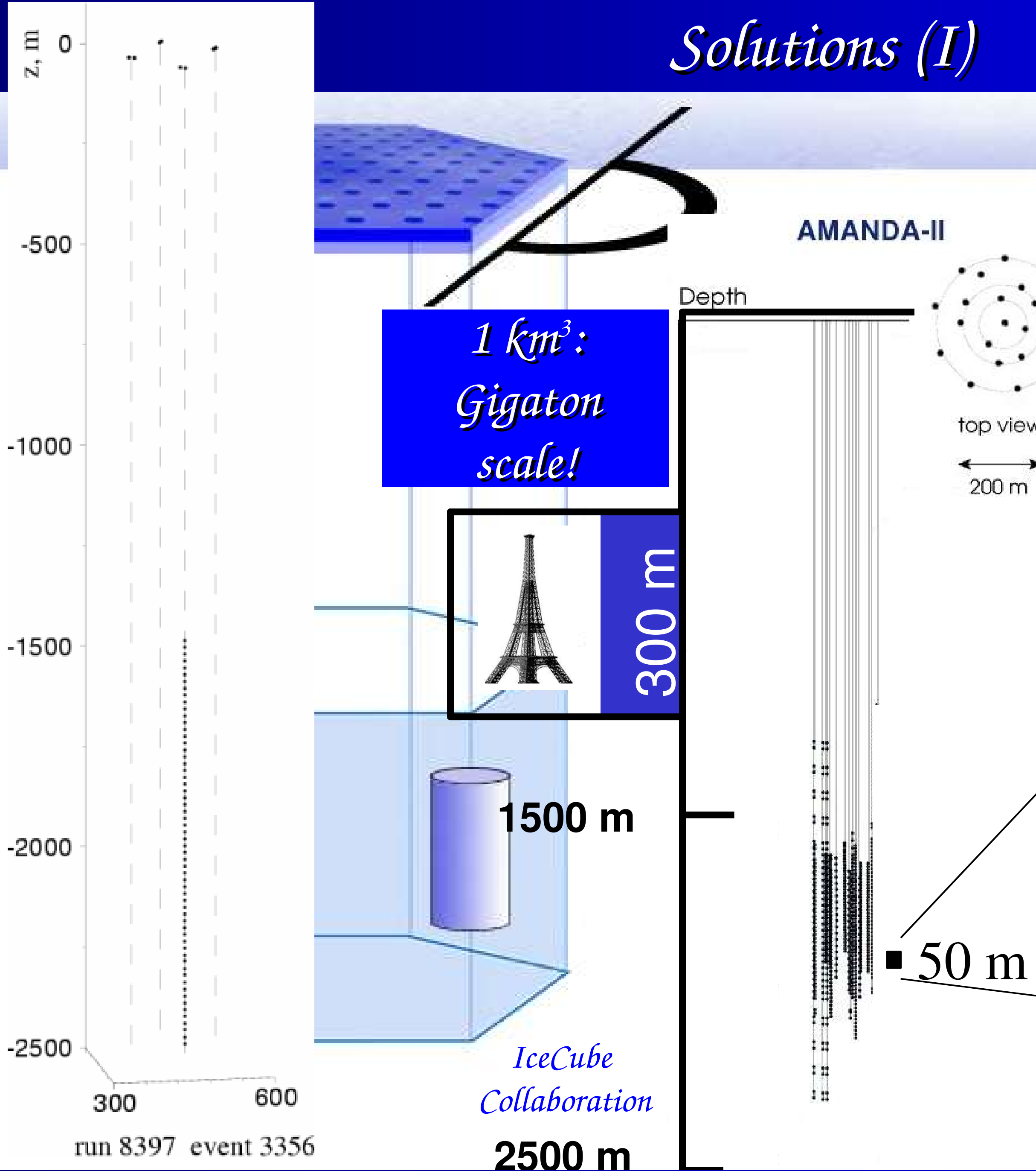
+)No absorption
(differently from **γ**)

+) HE**ν** guaranteed
(HECR & HE**γ** observed**)**

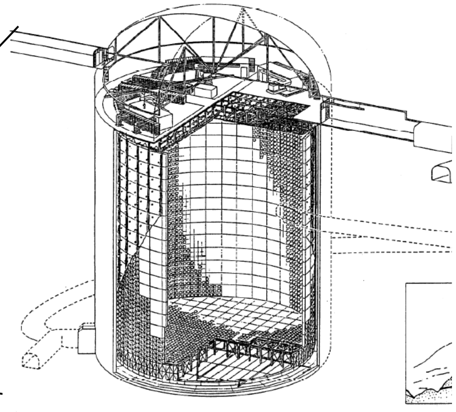
Main problem
-)Small **σ**



Solutions (I)

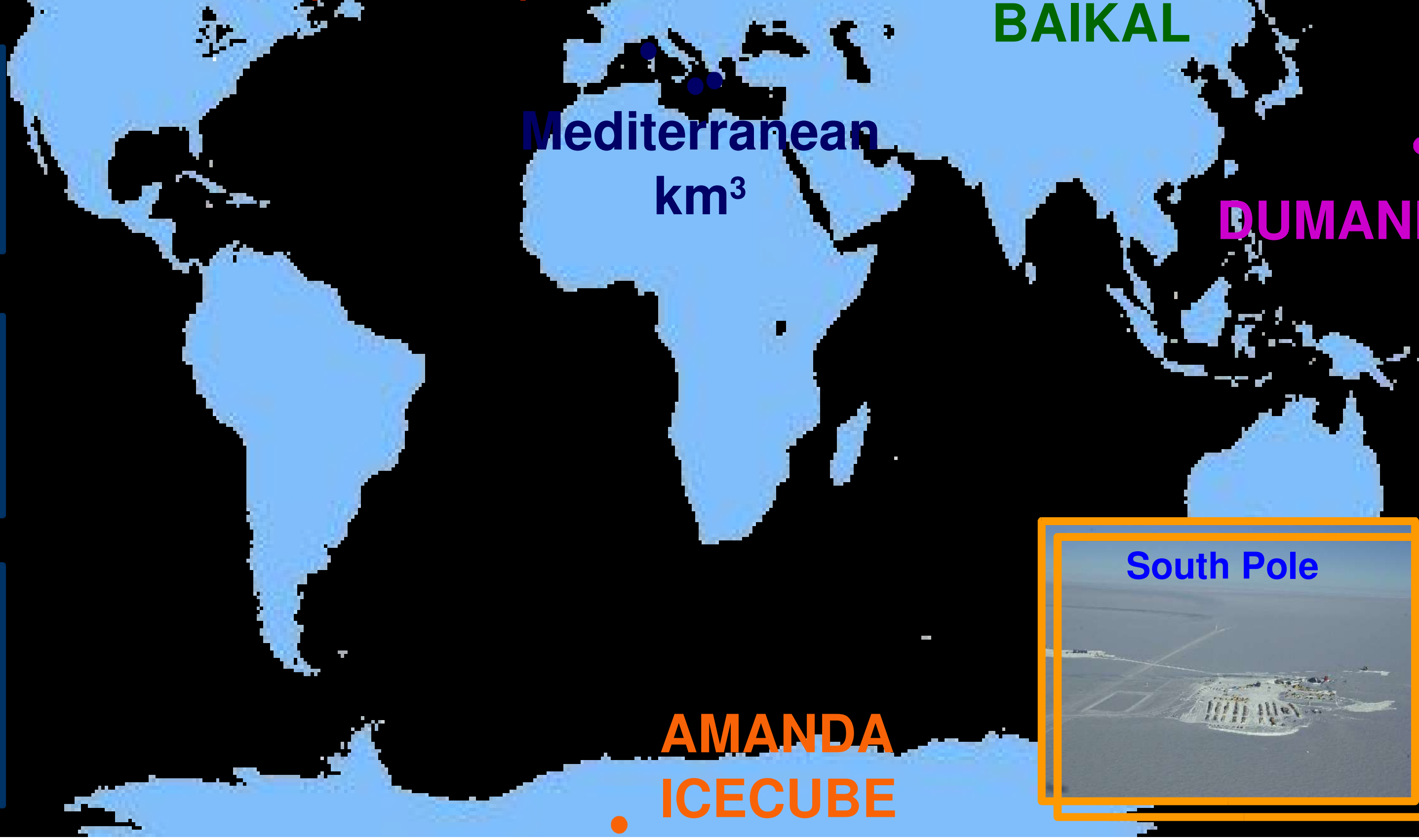


- huge volumes
- sparse instrumentation
- natural media



Status of Optical Cherenkov Telescopes

80's:	DUMAND R&D
90's:	BAIKAL, AMANDA, NESTOR
2k's:	ANTARES, NEMO R&D
<2010:	ICECUBE (km^3 at the SouthPole)
......?	Mediterranean km^3 (Km3Net)



Flavour discrimination (I)

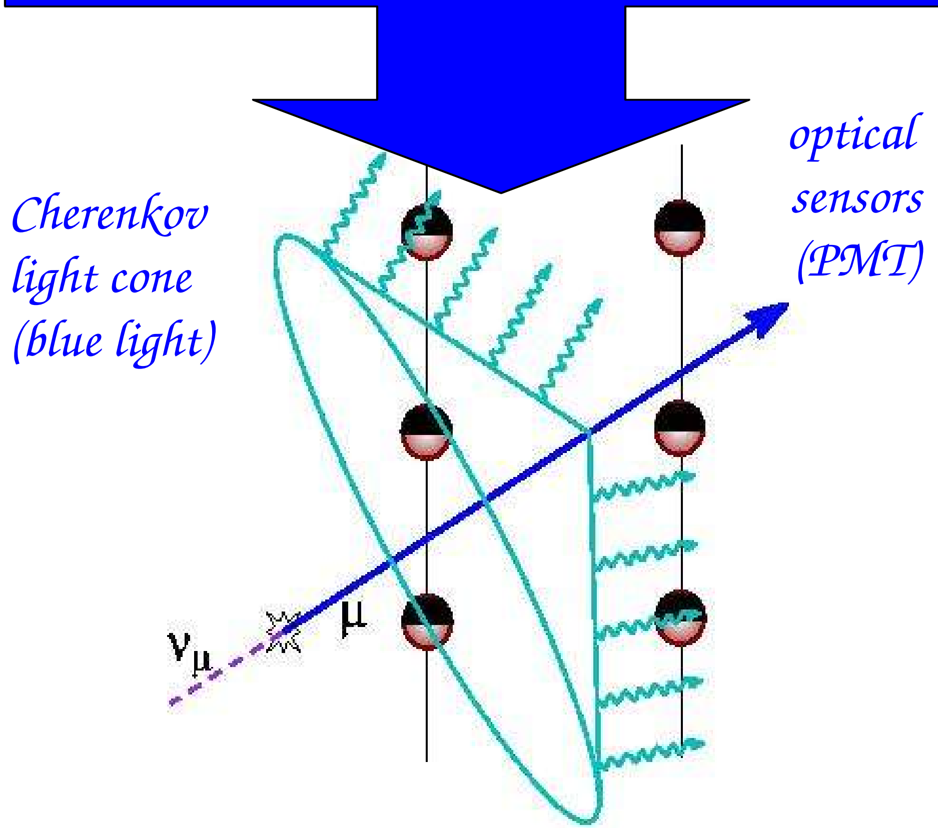
1^{st} detection channel: O(km) μ tracks

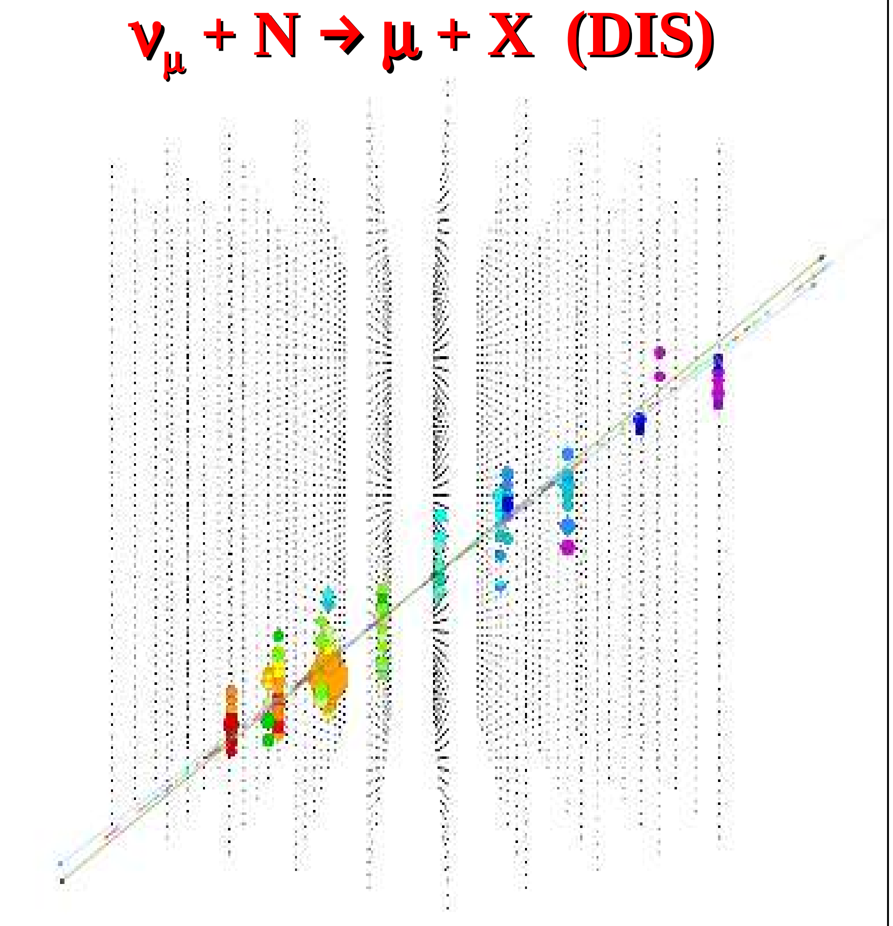
directional error: ~ 1°

$\sigma\,[\log_{10}(E/TeV)]$: ~ 0.3

coverage: **2π**

energy range: ~ 50 GeV to 100 PeV





Flavour discrimination (II)

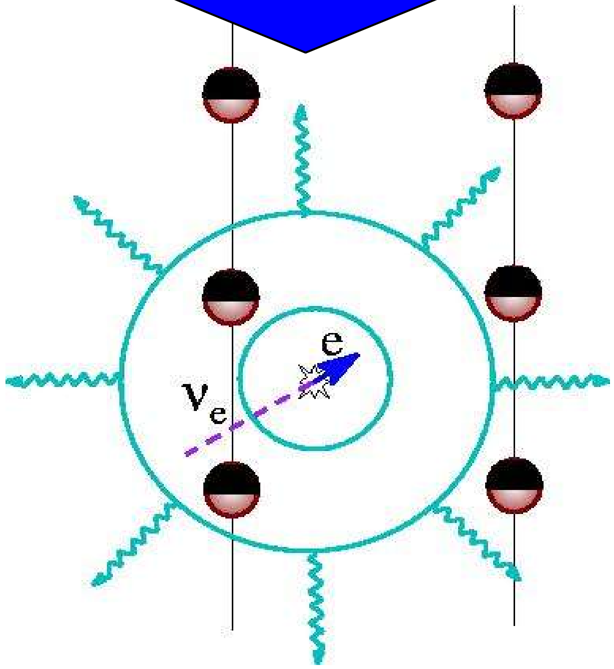
2^{nd} detection channel:
cascades from ν_e & ν_τ CC + all flavors NC

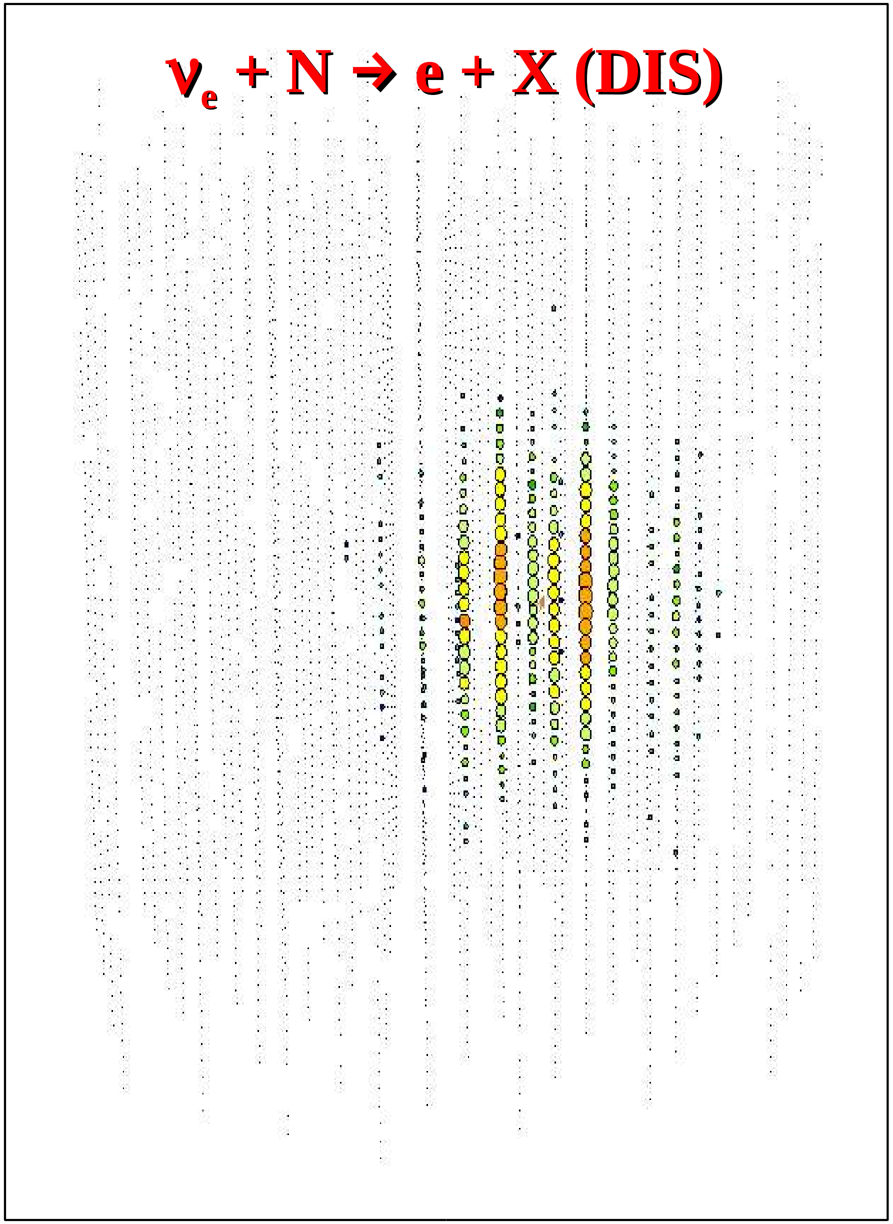
directional error: ~ 10-40°

$\sigma\ [\log_{10}(E/TeV)]$: ~ 0.1

coverage: **4π**

energy range: ~ 1 TeV to 100 PeV





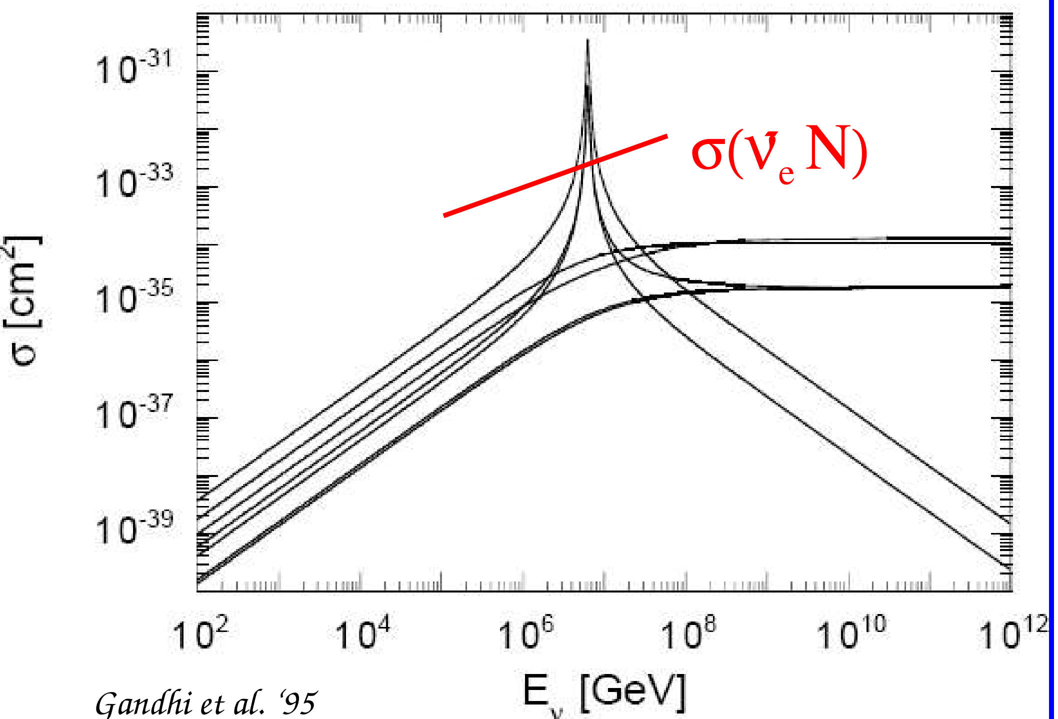
Flavour discrimination (III)

"Glashow Resonance"

$\bar{\nu}_e + e^- \rightarrow W \rightarrow$ *anything*

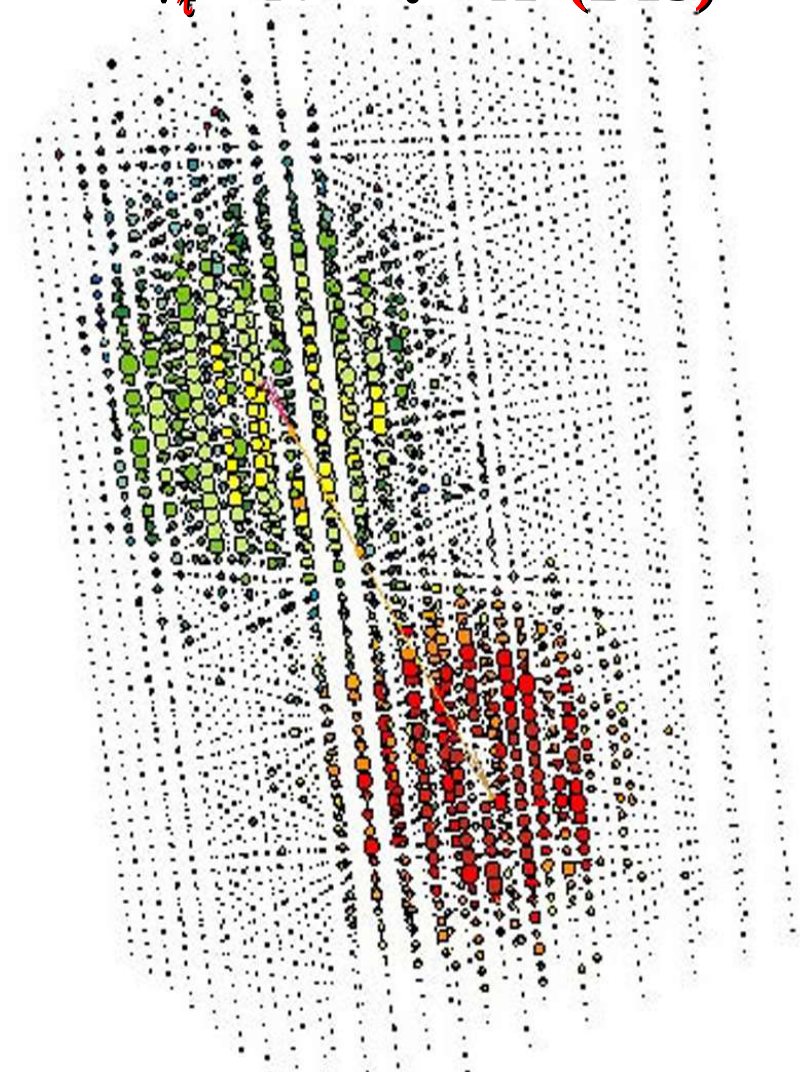
Unique to $\bar{\nu}_e$

σ *enhanced at* $E \approx 6.3$ *PeV*



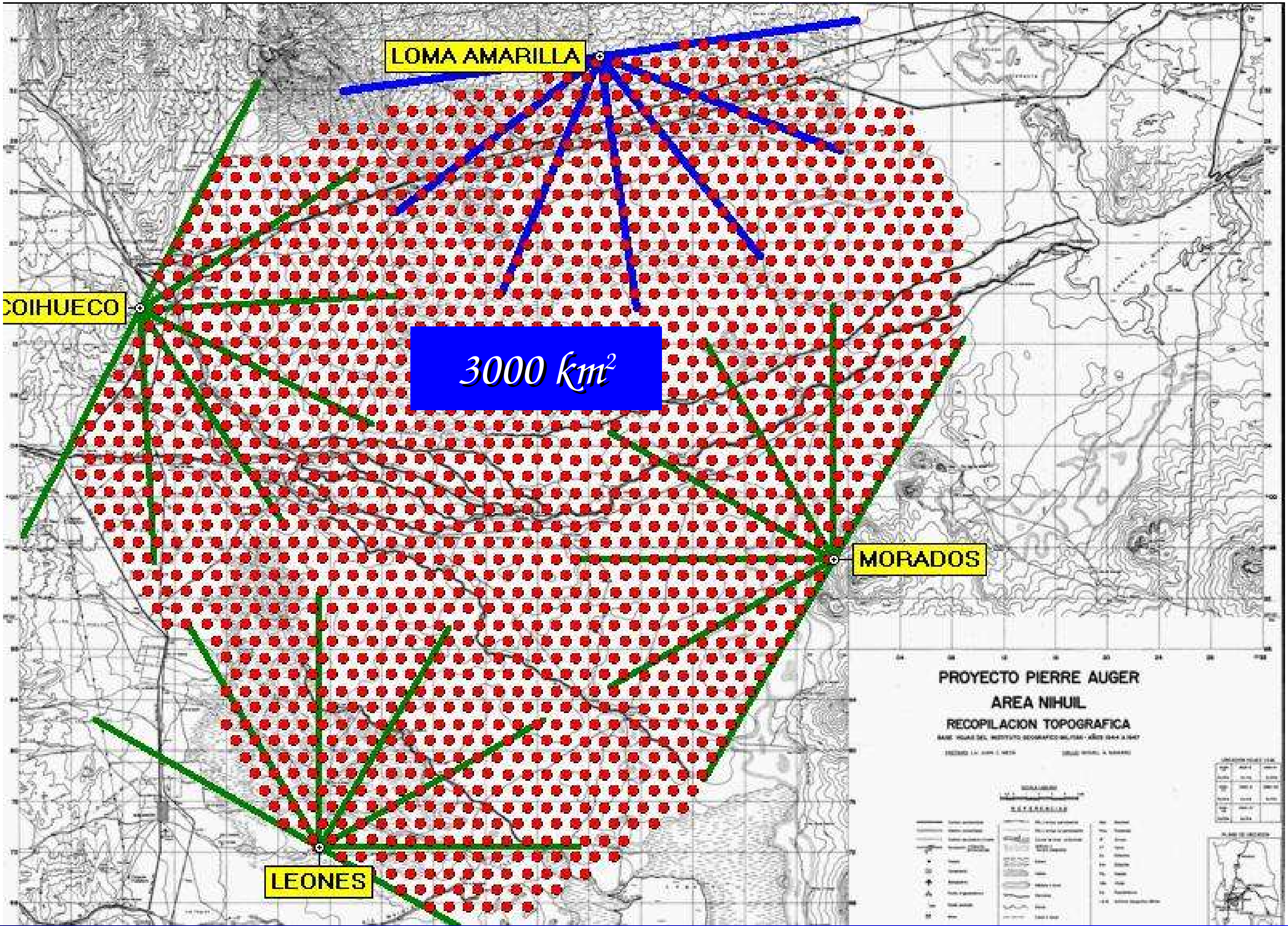
Gandhi et al. '95

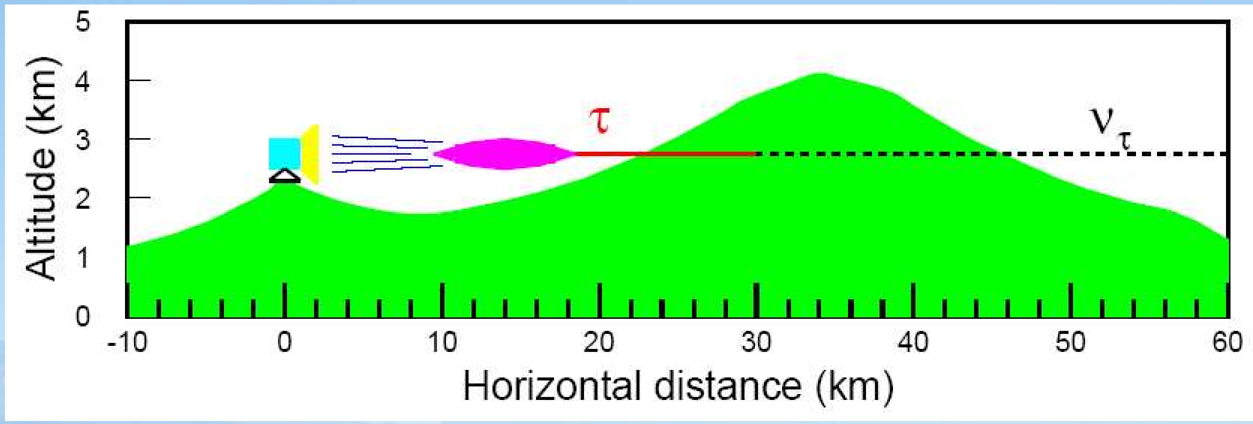
$\nu_\tau + N \rightarrow \tau + X$ **(DIS)**

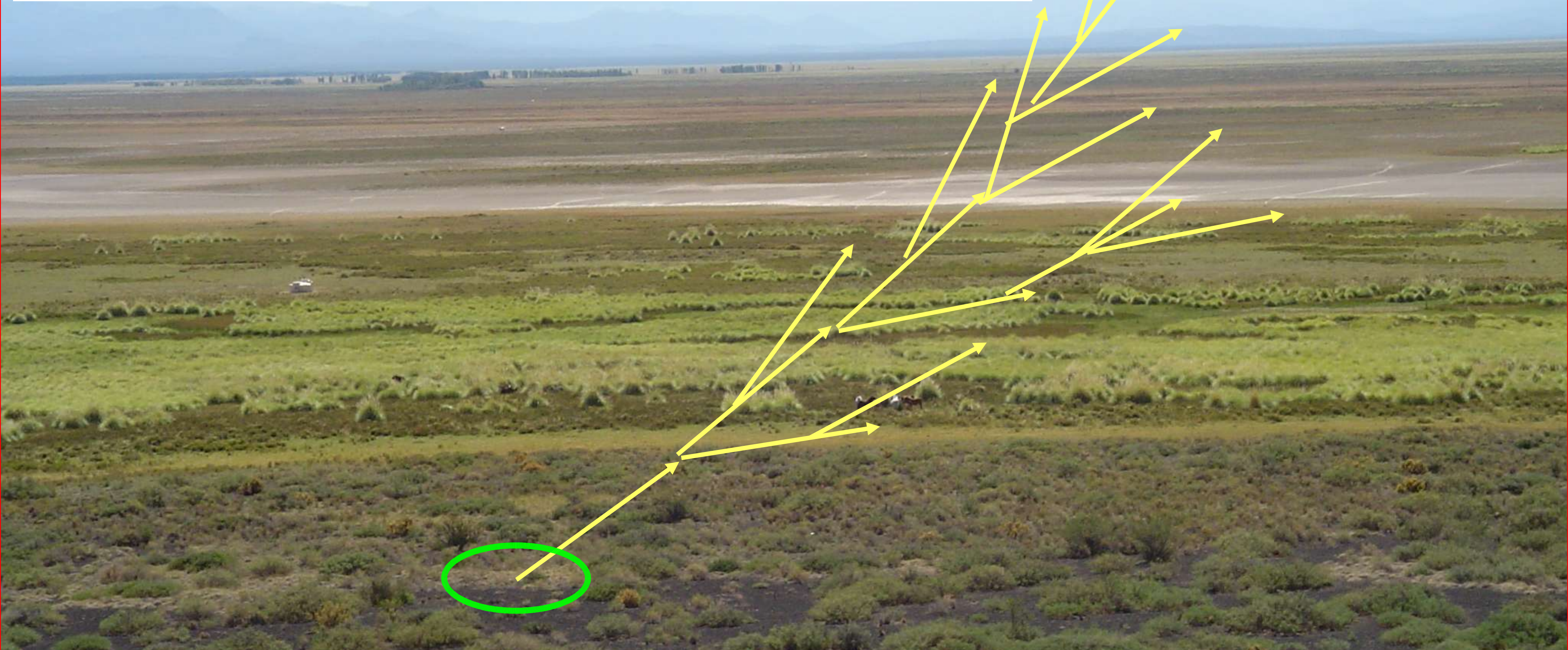


E > few PeV

Solutions (II)



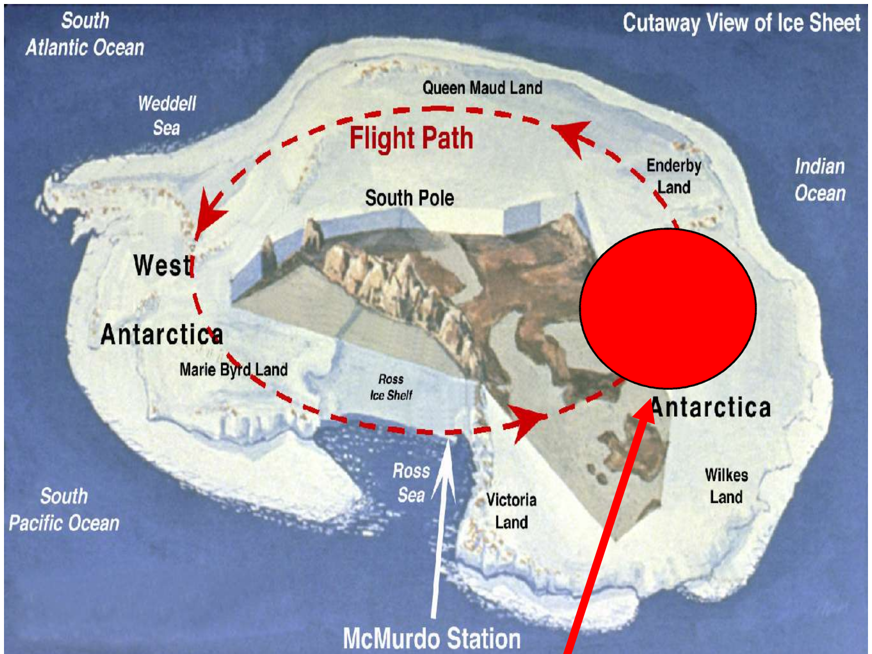




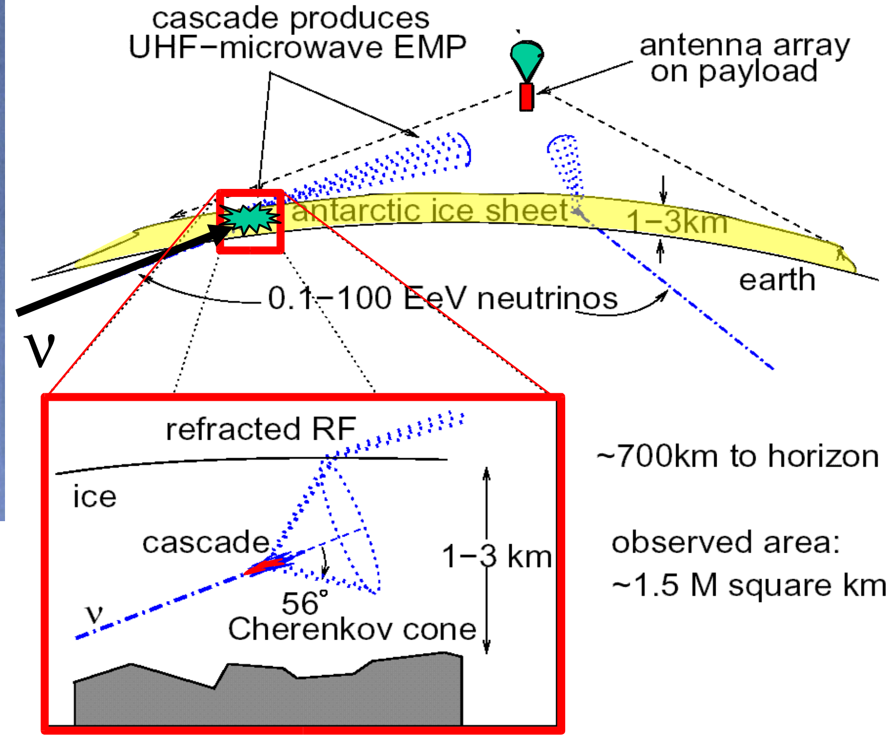
Upgoing ν_τ shower (seen by Los Leones

Solutions (III)

***AN**tarctic **I**mpulsive **T**ransient **A**ntenna*



600 km radius,
1.1 million km²



~700km to horizon

observed area:
~1.5 M square km

ν-mixing at ν-telescopes

ν-telescopes and ν-mixing

Astrophysical ν fluxes come from

$pp \rightarrow \pi X$

$p\gamma \rightarrow \pi X$

flavour ratios at source $\rightarrow \phi_e : \phi_\mu : \phi_\tau \approx 1/3 : 2/3 : 0$

at Earth after oscillations $\rightarrow \phi_e : \phi_\mu : \phi_\tau \approx 1/3 : 1/3 : 1/3$

quite insensitive to mixing parameters

$d_{\mathrm{source}} >> L_{\mathrm{osc}} \rightarrow$ *no sensitivity to* Δm_{sol}^2 , Δm_{atm}^2

Standard Paradigm: Neutrino mixing studies hopeless at high energy neutrino telescopes

I shall try to argue that this is misleading!

ν-telescopes and ν-mixing

1. Standard oscillation phenomenology "rescues" signals, allowing some interesting measurements

1. Matter effects might imply observations sensitive to Δm^2's, e.g. to hierarchy

3. Input from ν-mixing very important for diagnostics of astrophysical sources

↕

4. "Peculiar" (but not "exotic"!) neutrino sources may exist sensitive to mixing parameters (including θ_{13} and δ_{CP})

Only standard oscillation scenarios considered!

A "rescued" signal: The Galactic diffuse ν_τ

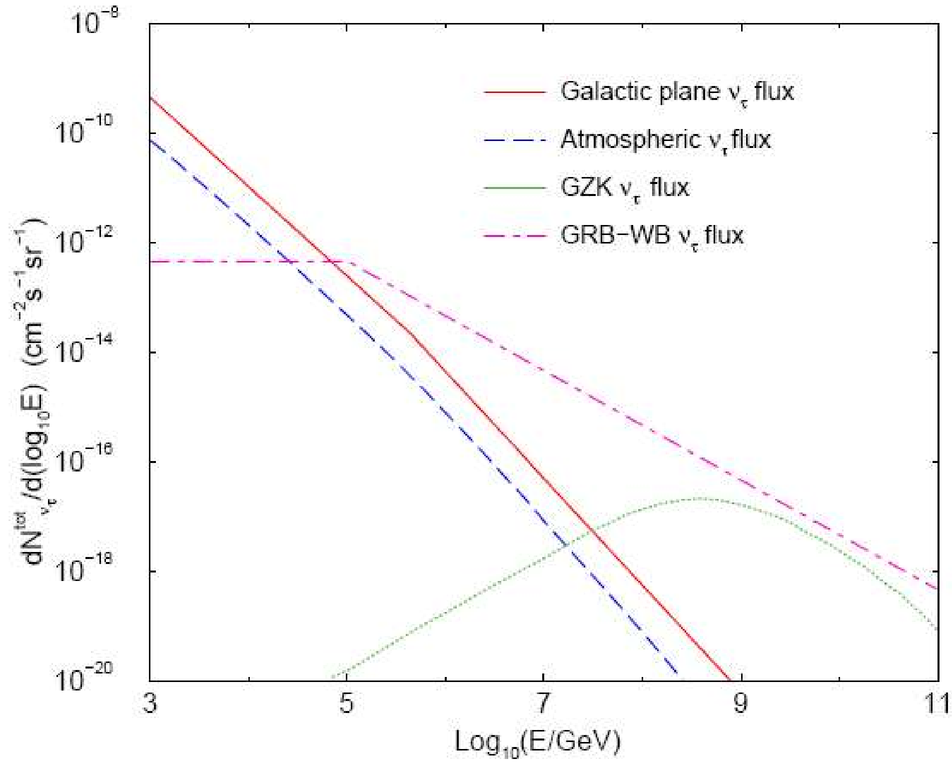
ν-flux from CR hitting Galactic matter develops a large ν_τ-component via oscillations.

Atmospheric ν background is

- *softer (relevant energy losses of mesons)*
- *ν_τ-suppressed (prompt ν_τ)*

$L_{osc}(E \approx$ TeV-PeV) is too large

H. Athar et al. APP 18 (2003) 581



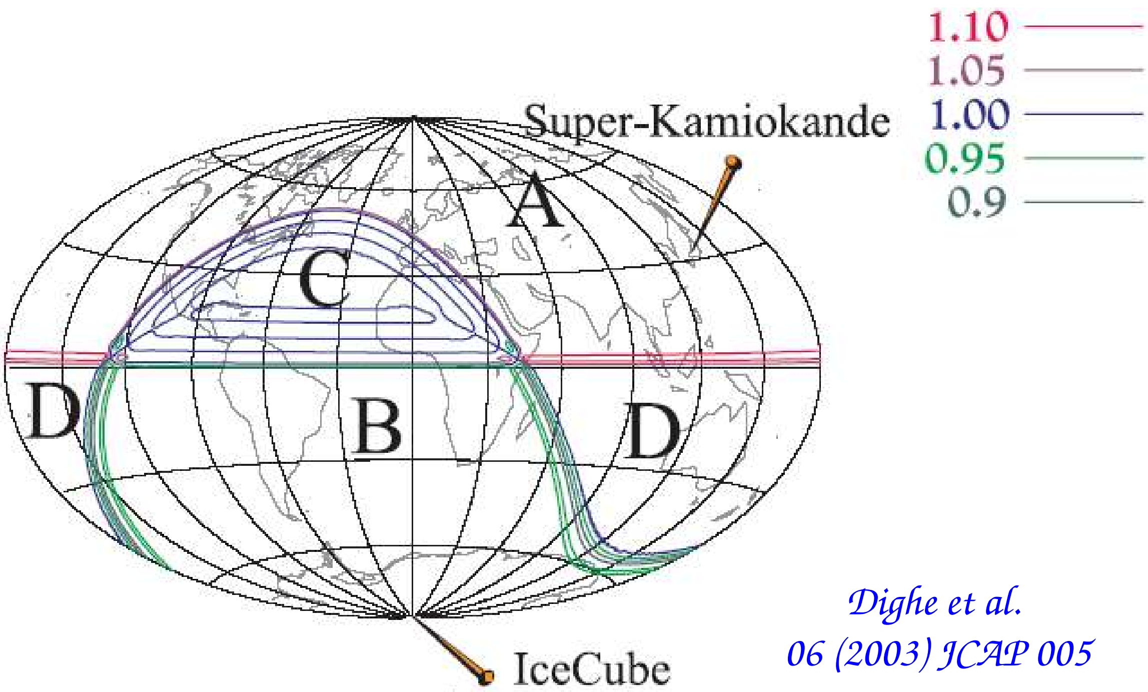
Event rate of $O(1\ yr^{-1}\ sr^{-1})$ for two separable and contained showers with $E \approx$ PeV in a km^3 ν-telescope

Independent confirmation of the (large) mixing in the $\mu-\tau$ sector via ν_τ appearence

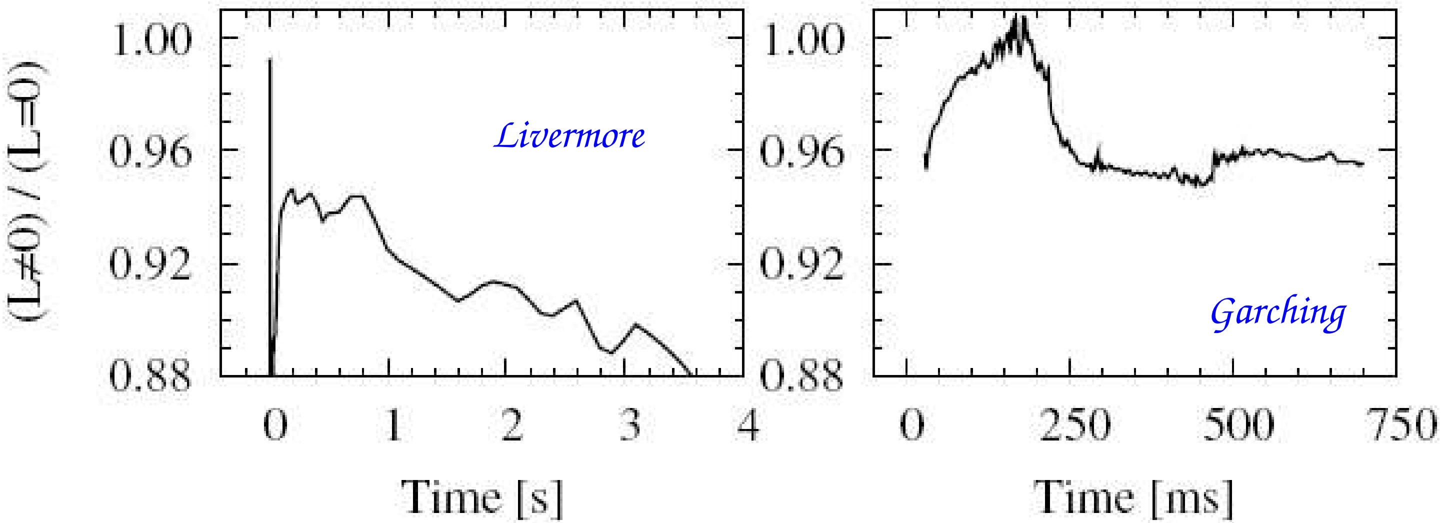
Earth matter effect with a SN at IceCube

Flux vs. time at IceCube + SK (or HK) can detect Earth matter effects (normal hierarchy and $\sin^2 \theta_{13} > 10^{-3}$)

Exploits high statistics for a galactic SN



Dighe et al. 06 (2003) JCAP 005



ν-telescopes, the Glashow resonance and θ_{12}

"Standard" astrophysical sources produce both ν and $\bar{\nu}$ via

$$pp \rightarrow \pi X$$

$$p\gamma \rightarrow \pi X$$

Both give flavour ratios at production

$$\phi_e : \phi_\mu : \phi_\tau \approx 1/3 : 2/3 : 0$$

but $p\gamma$ mainly gives ν_e (via π^+), while pp almost equally ν_e and $\bar{\nu}_e$

The measurable ratio

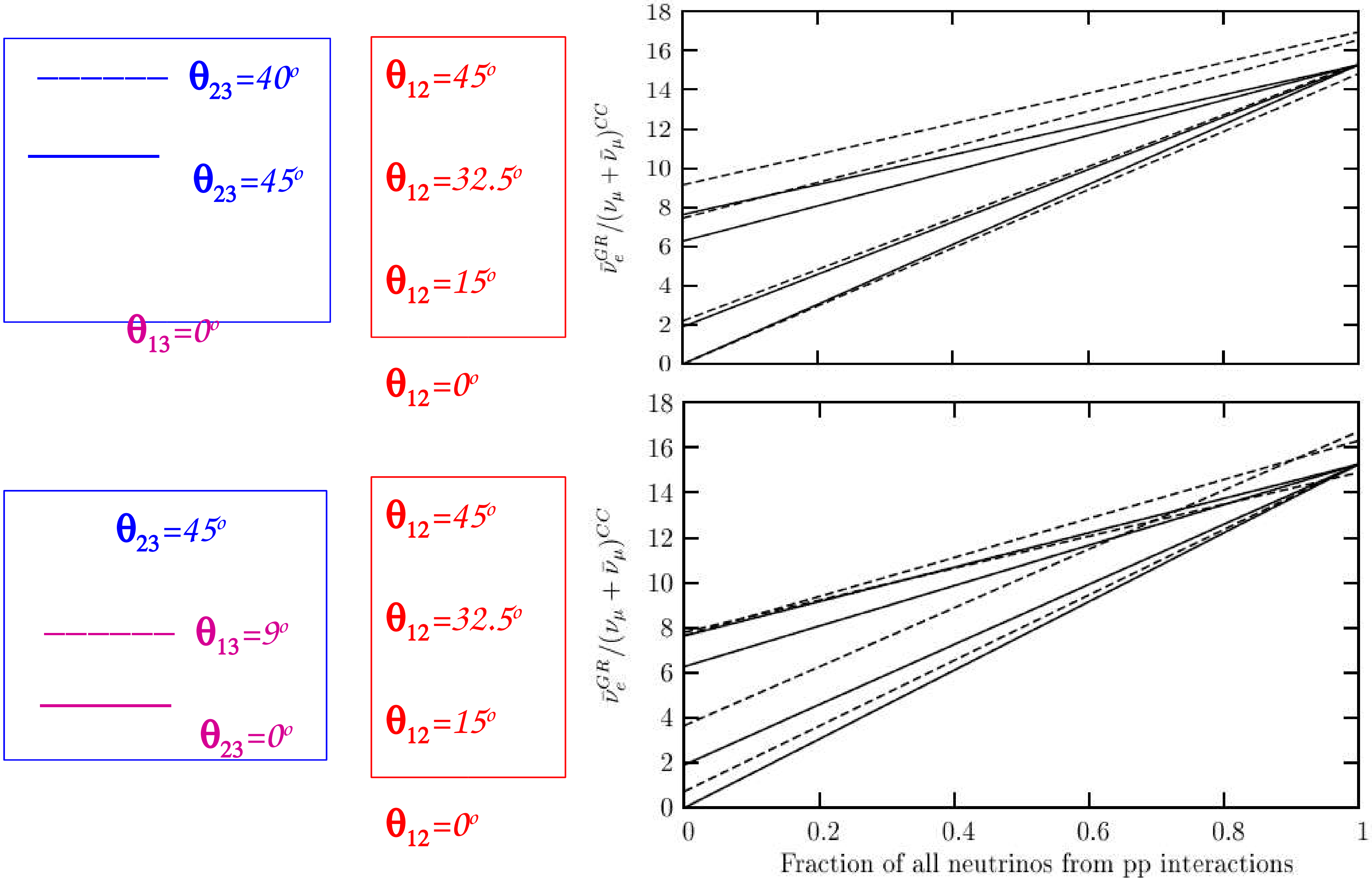
$$\mathcal{R}^{\bar{GR}} \equiv \bar{\nu}_e^{GR} / (\bar{\nu}_\mu + \nu_\mu)^{CC} \approx 15[\mathrm{Sin}^2\, 2\theta_{12} + \kappa(1 - 0.5\, \mathrm{Sin}^2\, 2\theta_{12})]$$

($\theta_{13} = 0^o$ and $\theta_{23} = 45^o$)

is sensitive both to mixing angles (mainly θ_{12}) AND to the production mechanism (% of pp "contamination" $\equiv \kappa$)

(Bhattacharjee & Gupta, astro-ph/0501191)

ν-telescopes, the Glashow resonance and θ_{12}



"Peculiar" high energy neutrino (re)sources

1. neutrons beams from nuclear dissociations → pure $\bar{\nu}_e$ beam

2. pion beams from muon damped sources → pure $\nu_\mu + \bar{\nu}_\mu$ beam

In both cases, the observable ratio of μ tracks to e+τ showers

$$\mathcal{R} = \frac{\phi_\mu}{(\phi_e + \phi_\tau)}$$

is sensitive to crucial information of the neutrino mixing matrix !!!

P.S. & M. Kachelrieß PRL 94, 211102 (2005) [hep-ph/0502088],

P.S., work in progress

Neutrino Mixing - Probabilities

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{\rm CP}} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta_{\rm CP}} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta_{\rm CP}} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta_{\rm CP}} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta_{\rm CP}} & c_{13}c_{23} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Mixing Matrix U

$s_{lk} \equiv \sin\theta_{lk}$, $c_{lk} \equiv \cos\theta_{lk}$

- *Matter effects negligible*
- *$d_{\text{source}} >> L_{\text{osc}}$: Terms sensitive to Δm^2, sign(δ_{CP}) average out*
- *Also imply equal expressions for neutrinos and antineutrinos*

$$P_{\alpha\beta} \equiv P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 2\sum_{j>k} \mathrm{Re}(U_{\beta j}U^*_{\beta k}U^*_{\alpha j}U_{\alpha k})$$

Flavor ratios at detector

$$\phi^D_\beta = \sum_\alpha P_{\alpha\beta}\phi_\alpha$$

Flavor ratios at source

"Galactic β-beams"

Sensitivity to θ_{13} (and θ_{23})

$$\mathcal{R} \equiv \frac{\phi_\mu}{(\phi_e + \phi_\tau)} = \frac{P_{e\mu}}{P_{ee} + P_{e\tau}}$$

$$P_{ee} \approx \frac{5}{8} - \frac{5}{4}\theta_{13}^2$$

$$P_{e\mu} \approx \frac{3}{16} + \frac{\sqrt{3}}{8}\theta_{13}\cos\delta_{CP} + \frac{5\theta_{13}^2}{8}$$

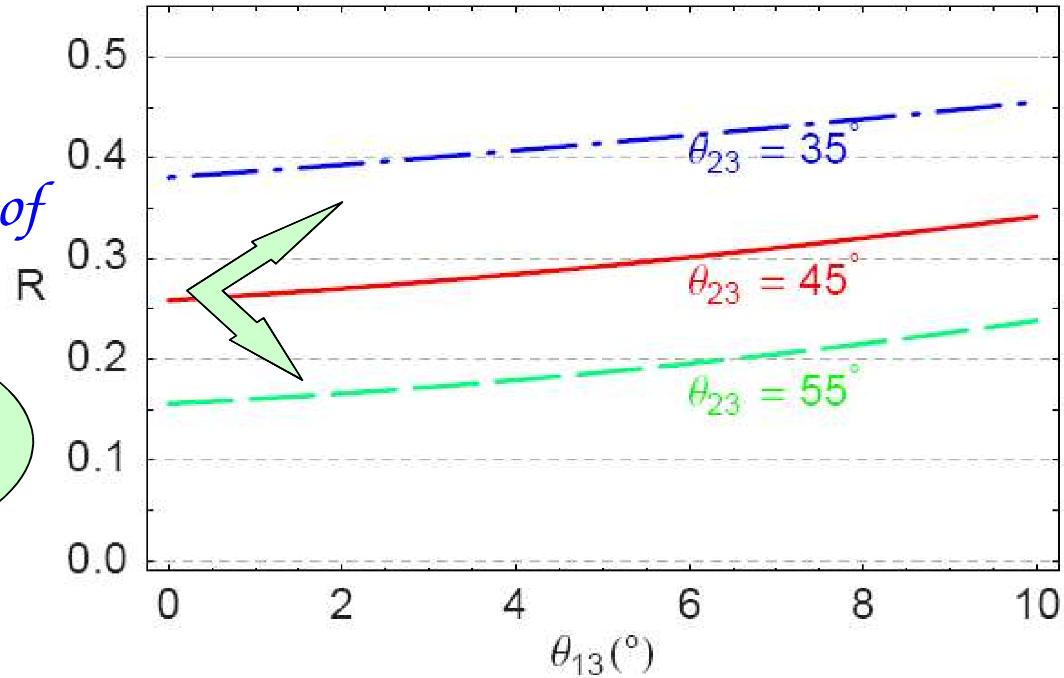
$$P_{e\tau} \approx \frac{3}{16} - \frac{\sqrt{3}}{8}\theta_{13}\cos\delta_{CP} + \frac{5\theta_{13}^2}{8}$$

$\theta_{12}=\pi/6$
$\theta_{23}=\pi/4$

Variation of order 25-50% in $0^o < \theta_{13} < 10^o$, depending on θ_{23} ($\theta_{12}=32.5^o$, best case $\delta_{CP}=0$)

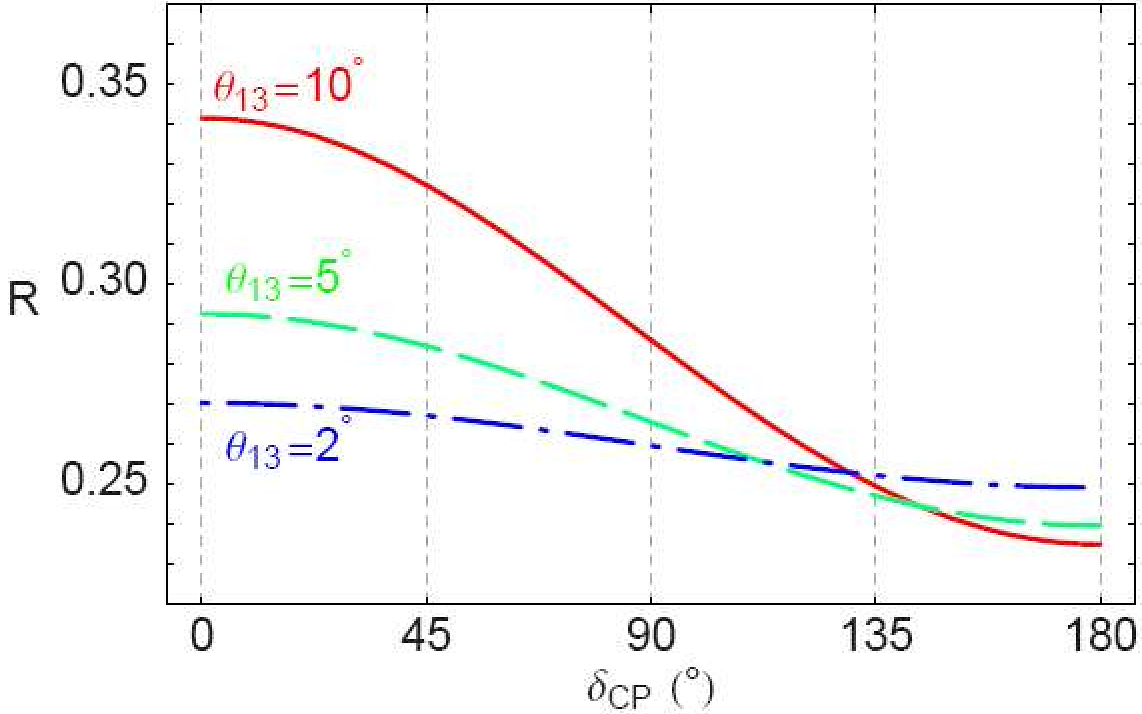
For $\theta_{23}=45^o$, $\mathcal{R}$ is reduced even to ½ of the canonical $\mathcal{R}=0.5$

Note the octant dependence!



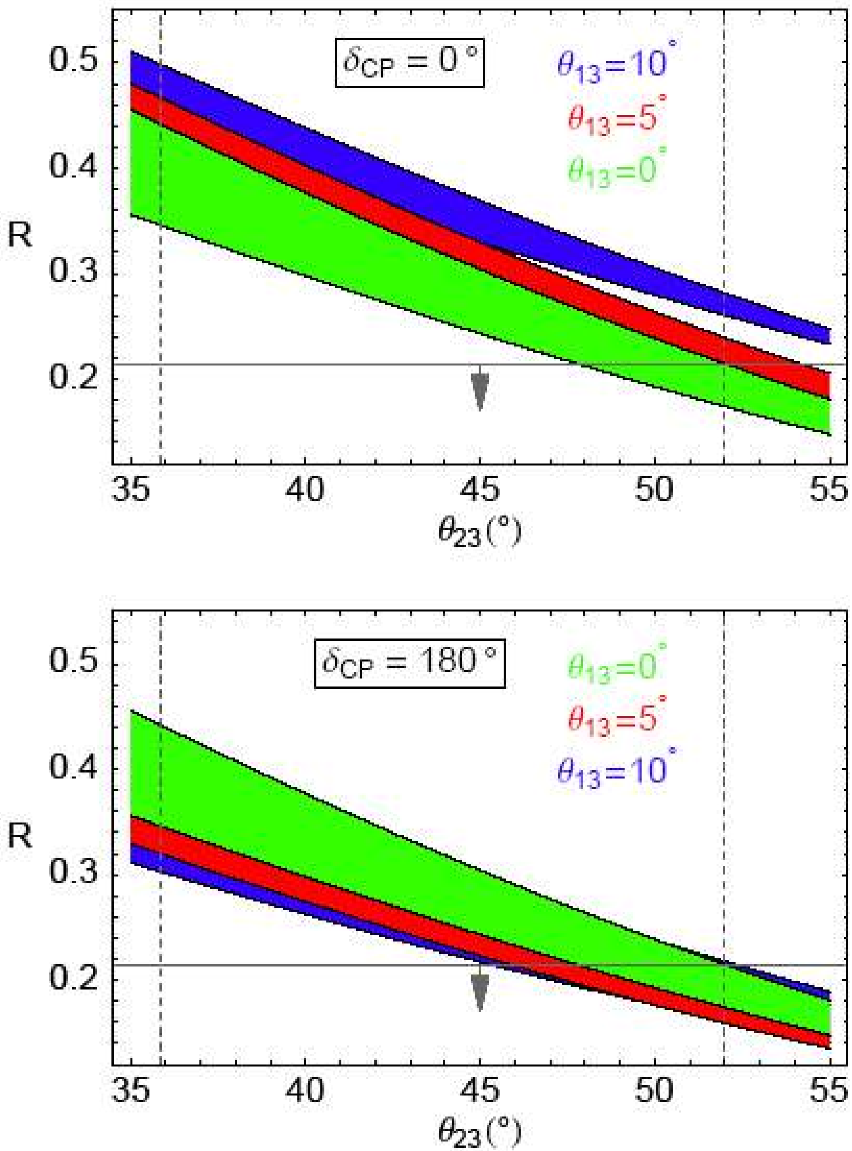
Sensitivity to δ_{CP}

For experimental best fit θ_{12}=32.5° and θ_{23}=45°, the flux ratio has a maximal variation of about 30%



NOTE: only sensitive to Cos (δ_{CP}) [CP-even term] not "direct" observation of CP-violation

Determination of the octant of θ_{23}



$$\mathcal{R} = \frac{\mathcal{P}_{e\mu}}{\mathcal{P}_{ee} + \mathcal{P}_{e\tau}}$$

$$P_{ee} \approx \frac{5}{8},$$

$$P_{e\mu} \approx \frac{3}{8} c_{23}^2 + \frac{\sqrt{3}}{4} s_{23}\, c_{23}\, s_{13}\, c_\delta,$$

$$P_{e\tau} \approx \frac{3}{8} s_{23}^2 - \frac{\sqrt{3}}{4} s_{23}\, c_{23}\, s_{13}\, c_\delta,$$

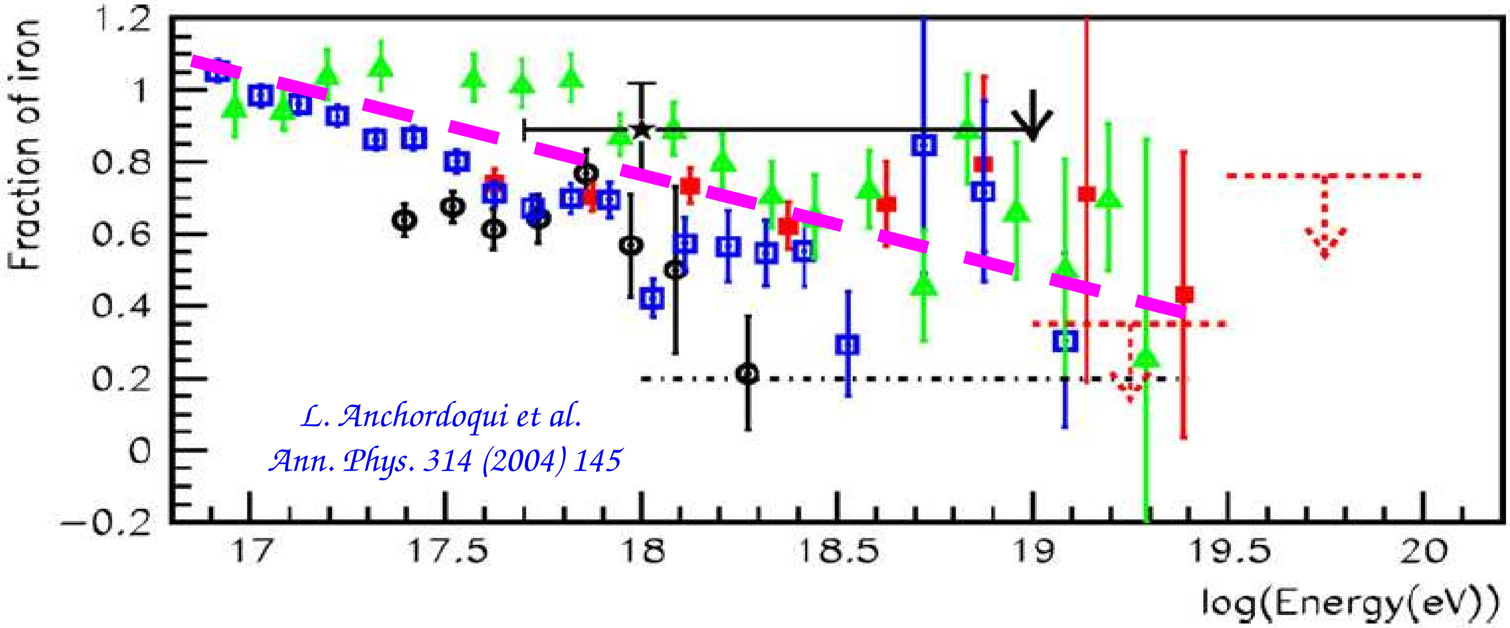
$\mathcal{R} < 0.21 \rightarrow \theta_{23} > \pi/4$

Backgrounds can only increase $\mathcal{R}$!

Model-independent statement

Neutrinos from nuclei in the Galaxy

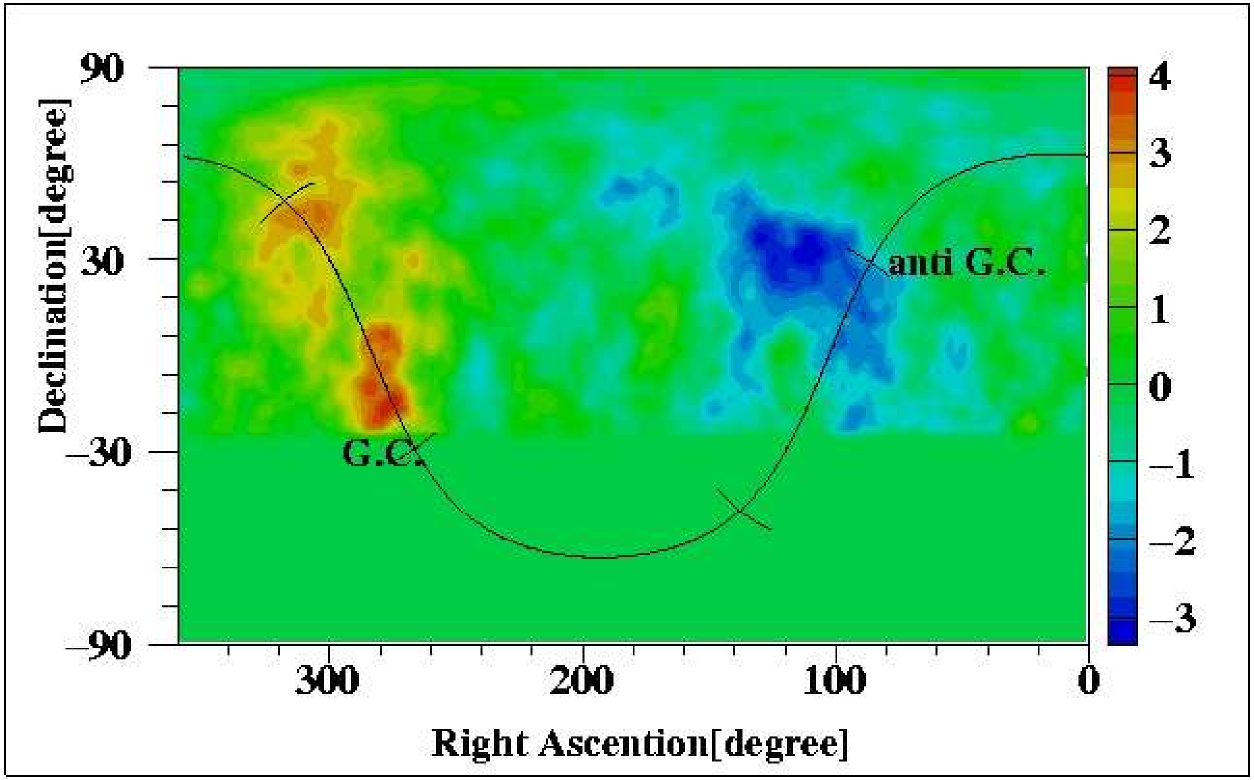
In cosmic rays, at E ≈ O(1 EeV) a transition between High-Z nuclei of the Galactic spectrum (acceleration and confinement requirements are alleviated) and p-dominated Extragalactic contribution is expected. Recent CR data support this scenario



n from nuclei dissociations in matter and γ–fields in (a few) galactic accelerators might become visible at EeV.
Favored regions: Nuclear Bulge, dense clouds (high B-field) …

Hint: A Galactic Plane excess in EeV Cosmic Rays

AGASA reported a 4% excess in UHECR around 10^{18} eV (1 EeV) from a couple of hot-spots in the galactic disk

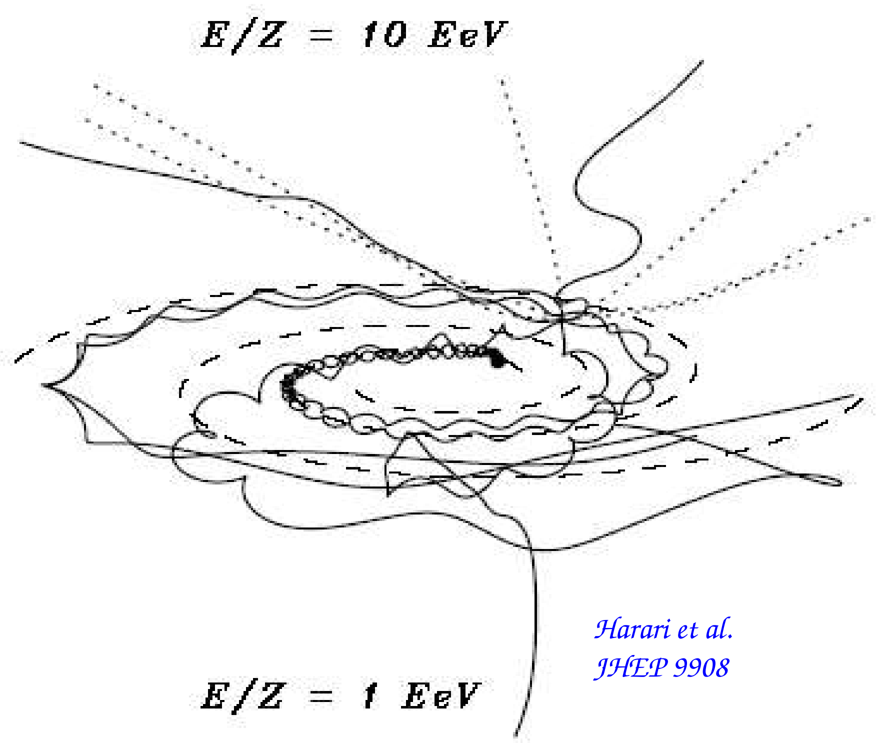


Similar, indepentent hints also from SUGAR and Fly's Eye (but negative results from preliminary analysis of Auger data)

The birth of Galactic neutron Astronomy?

Neutrons are natural candidates to explain the signal

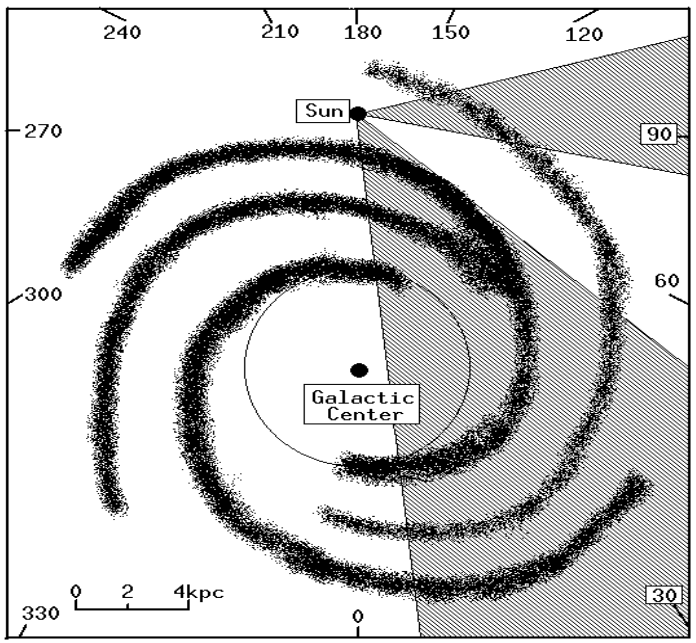
no GMF bending (huge for p too!)



Harari et al.
JHEP 9908

Energy-range of the Signal
≈ boosted n-lifetime

$$c\tau_n \approx 10\ kpc\ (E_n / EeV)$$



From Neutrons to Neutrinos

The existence of galactic neutron beams would imply

$\bar{\nu}_e$ fluxes up to the PeV from n-decay.

$(E_\nu / E_n \sim Q / m_n \sim 10^{-3} \rightarrow E_\nu \sim \text{PeV},\ \text{for}\ E_n \sim \text{EeV})$

If neutrons come from nuclear photodissociations on Optical/UV photons, the flux is likely to extend down to (at least) TeV region

This energy range nicely fits the energy-window accessible to ν-telescopes under construction.

Notice that n are undetectable as CR anisotropies below $E \sim 10^{17}$ eV: similar sources of lower Energy might show-up only in the $\bar{\nu}_e$ channel !!!

A model of galactic neutron beams

Detectability in IceCube

Normalizing to the CR anisotropy, ~ 20 events per year from Cygnus region in **IceCube** *(under construction at the South pole)*

Standard ν *oscillation phenomenology implies*

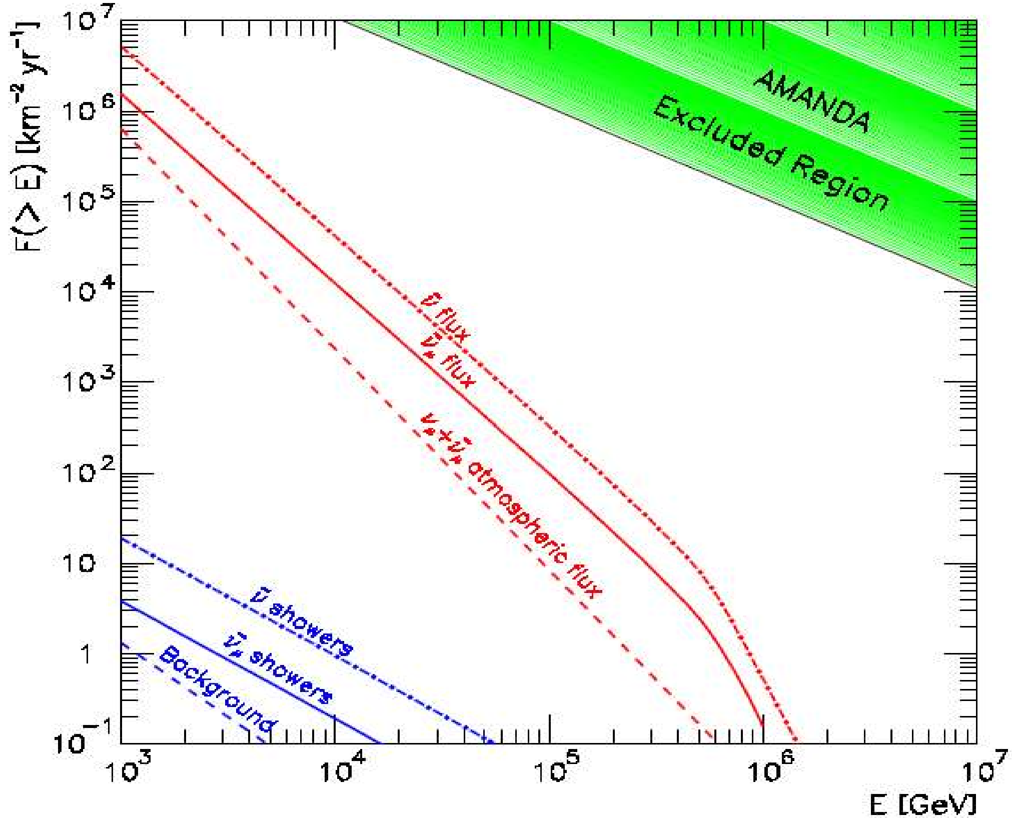
$\approx 4\,\nu_\mu$ */yr tracks in 0.7° circle*

(Atm. background is ~2.3 ν_μ */yr)*

$\approx 16\,\nu_e+\nu_\tau$ *showers/yr in 25°, cone, due to poor resolution.*

(Atm. background fluctuation is ~12 $\nu_e+\nu_\tau$*/yr)*

In a few years, IceCube should attain discovery sensitivity for $n \rightarrow \nu_e \rightarrow \nu_\mu$*!!!*



L. Anchordoqui, H. Goldberg, F. Halzen & T.J. Weiler PLB 593 (2004) 42

How large is the expected "pion contamination"?

Viable models of $A \rightarrow n \rightarrow \nu$ scenarios exist, e.g.:
Cygnus region: L. Anchordoqui et al. PLB 593 (2004) 42
SGR A East SN remnant: Grasso and Maccione [astro-ph/0504323]

From astrophysical data e.g. on the Cygnus region (e.g. UV γ density) and hadronic physics data (e.g. secondary population yields in hadronic interactions)

$$\nu_{\text{nuclear dissociation}} \approx 27\, \chi\, \nu_{\text{pp hadronic interactions}}$$

In this case, likely π contaminations to ν flux are at the O(10%) level $\rightarrow \Delta R \approx +0.02$ only!

Within the expected statistical accuracy of IceCube & at the same subleading level of other effects neglected in our estimate

Is this scenario falsifiable?

Normalizing the anisotropy to the "n-chain" model, $n \rightarrow \nu$–fluxes should easily observable in IceCube, with a detailed measurement in a decade.

If the π–chain dominates, the flux should be much higher, though with a flavour ratio of about 1:1:1

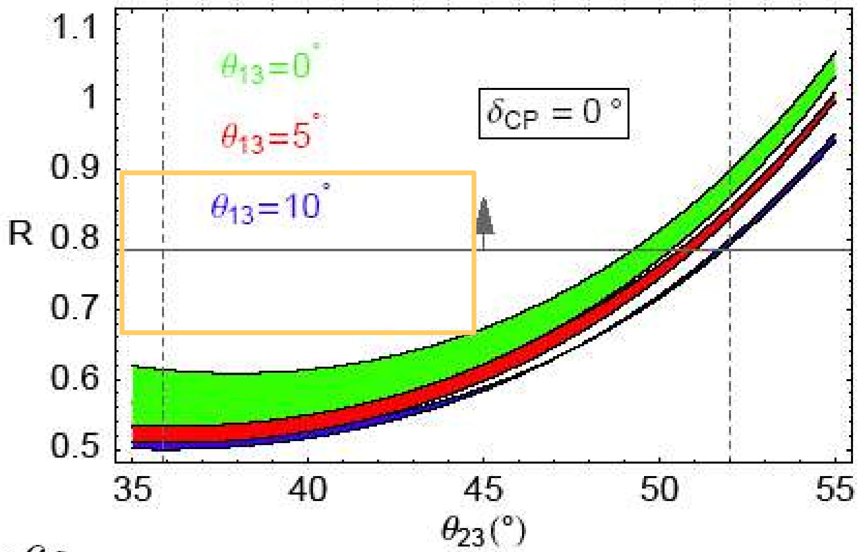
Also γ-rays constraints!

High ν flux and R=0.5 would disprove the dominance of $A \rightarrow n \rightarrow \nu$!

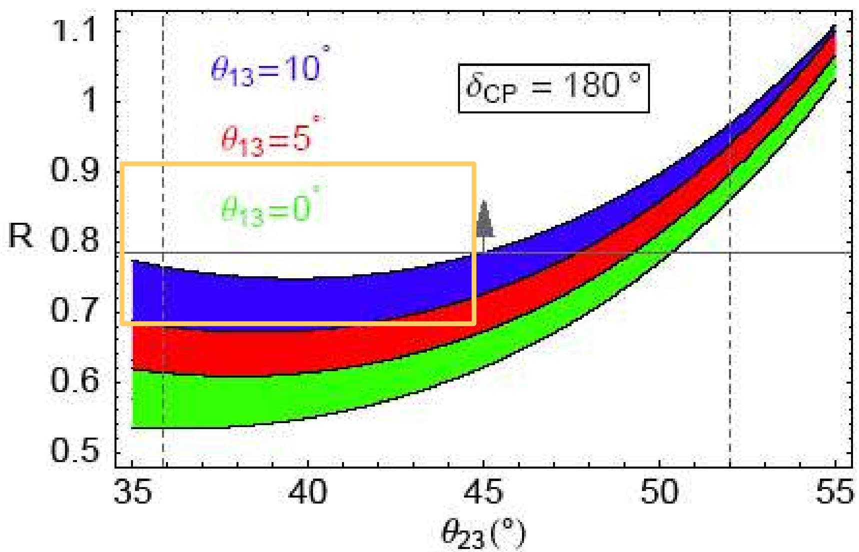
muon-damped sources

Sensitivity to the octant of θ_{23}

$$\mathcal{R} \equiv \frac{\phi_\mu}{(\phi_e+\phi_\tau)} = \frac{\mathcal{P}_{\mu\mu}}{1-\mathcal{P}_{\mu\mu}}$$



$$P_{\mu\mu} \approx 1 - \frac{3}{8}c_{23}^4 - 2c_{23}^2 s_{23}^2 - \frac{\sqrt{3}}{2} c_{23}^3 s_{23} s_{13} c_\delta .$$



$\mathcal{R}>0.78 \rightarrow \theta_{23} > \pi/4$

Backgrounds can only decrease $\mathcal{R}$!

Model-independent statement

Why pion beams?

Effective "pion beams" produced in sources where muons (but not pions) are damped sources → pure $\nu_\mu + \bar{\nu}_\mu$ beam

Boosted Lifetime $\propto E$

E.m. cooling time $\propto E^{-1}$ (Inv. Compton), E^0 (adiabatic expansion),…

Their ratio increases with E, at a certain ε_0 the particle is stopped before decaying.
The lifetime implies $\varepsilon_{0\mu} << \varepsilon_{0\pi}$

For AGN, π beams @ $O(10^6)$ TeV → unobservable at OCT
For GRB, π beams possibily @ O(10) TeV → optimal for OCT!!!

Flavour ratios can be used for astrophysical diagnostics

Kahsti & Waxman, PRL 95 (2005) 181101

Concluding remarks

Overview - I

Neutrino telescopes are optimized for astrophysical purposes, but they may have a potential for ν-mixing physics, too.

ν_τ appearence expected to be seen within 3-4 years (IceCube completed + 1 year of running)

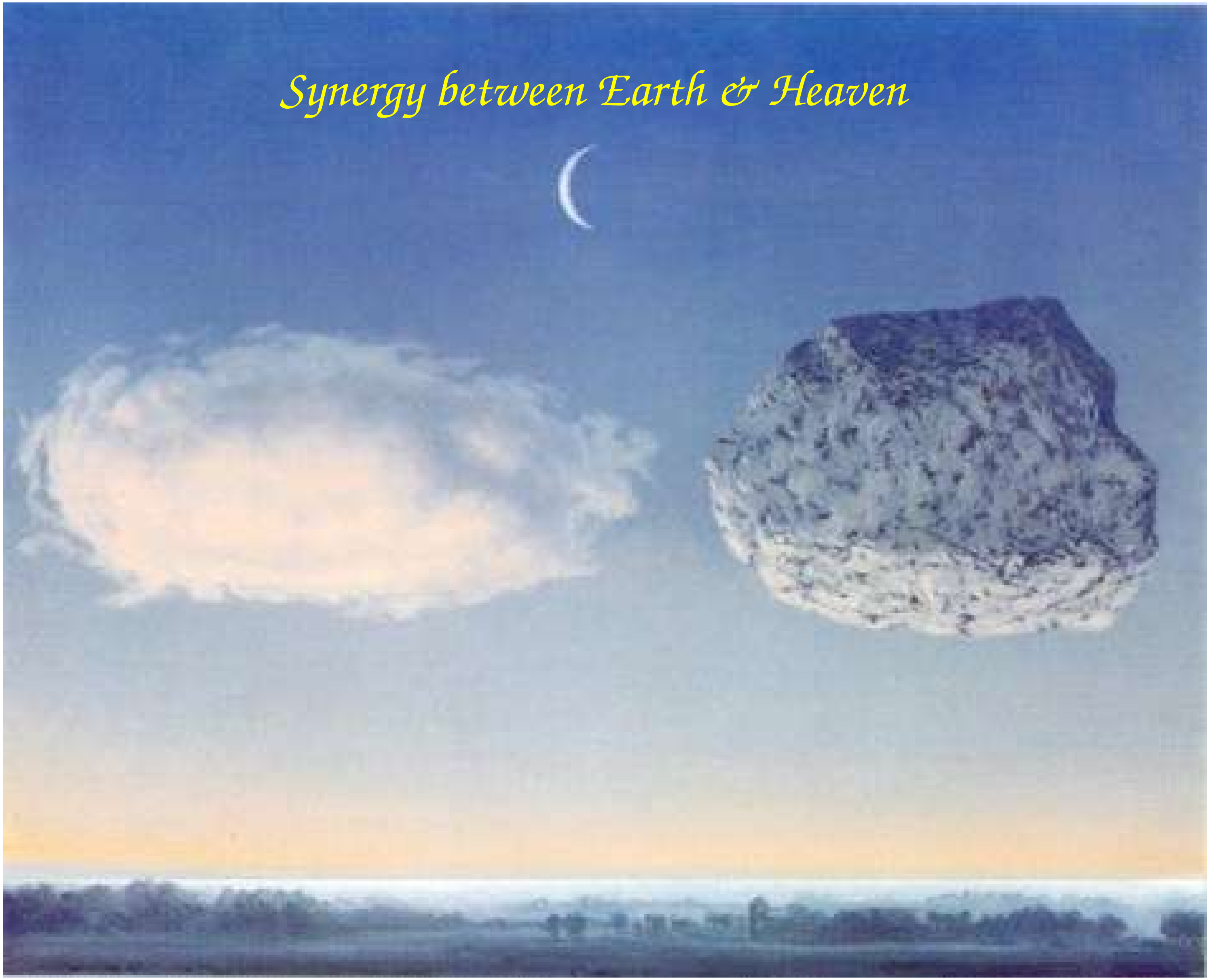
"Calorimentric" detection of a galactic core-collapse SN possible. Earth matter effect (and thus hierarchy/θ_{13}) possibly identified at IceCube+"HK", or +Mediterranean km^3

Overview - II

I showed that it is conceivable or even likely that Nature might provide "β-beams" (or pion beams) for free, that could be studied at ν-telescopes already in construction.

Measurable flavor ratios are sensitive to θ_{13}, δ_{CP}, and to the octant of θ_{23}. The latter is particularly suitable for a model-independent determination (if $\theta_{23} > \pi/4$)

Going beyond the paradigm of a "canonical" flavor equipartition would repropose at neutrino telescopes the fruitful synergy between neutrino physics and astrophysical diagnostics



THANK YOU!

Neutrino mixing parameters

Solar/Kamland

Best Fit: $Sin^2\,\theta_{sol}$ =0.29, Δm_{sol}^2=8.1 x 10^{-5} eV^2

3 σ range: 0.23 < $Sin^2\,\theta_{12}$ < 0.37, 7.3 x 10^{-5} <$\Delta m_{sol}^2/eV^2$ < 9.1 x 10^{-5}

Best Fit: θ_{sol} = 32.6°

3 σ range: 28.7 °< θ_{sol} <37.5°

Atmospheric/K2K

Best Fit $Sin^2\,\theta_{atm}$ =0.5, Δm_{atm}^2=2.2 x 10^{-3} eV^2

3 σ range 0.34 < $Sin^2\,\theta_{atm}$ < 0.66; 1.4 x 10^{-3} <$\Delta m_{atm}^2/eV^2$ < 3.3 x 10^{-3}

Best Fit: θ_{atm} = 45°

3 σ range: 35.7 °< θ_{sol} <54.3°

Global (CHOOZ+others)

Best Fit: $Sin^2\,\theta_{13}$ =0

3 σ range: $Sin^2\,\theta_{13}$<0.047,

θ_{13} <12.5°

Maltoni et al.,
NJP 6 (2004) 122

σ(νN) vs. E

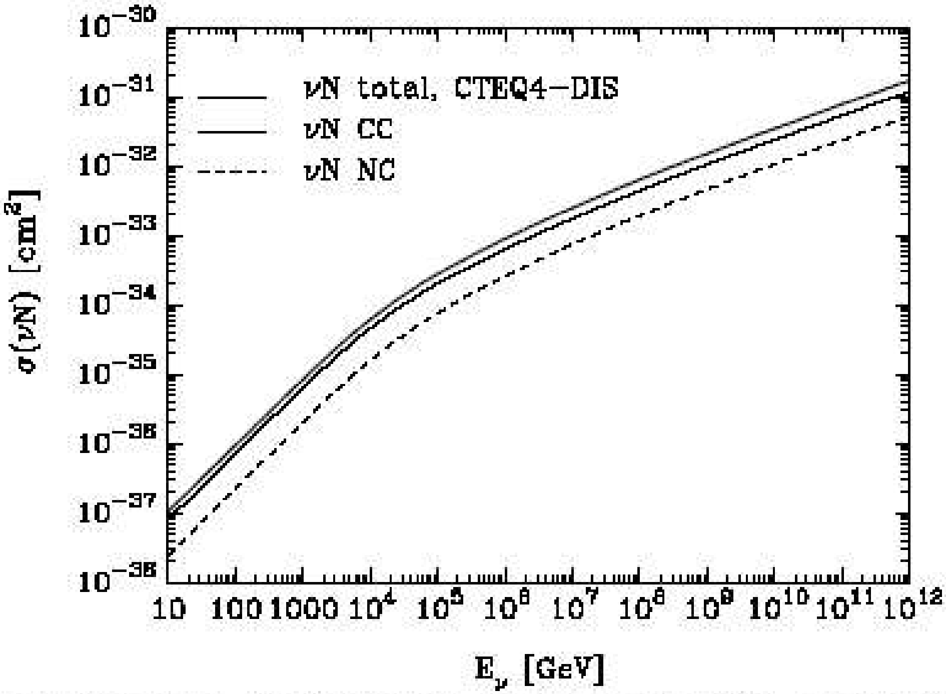


FIG. 1. Cross sections for $\nu_\ell N$ interactions at high energies, according to the CTEQ4–DIS parton distributions: dashed line, $\sigma(\nu_\ell N \rightarrow \nu_\ell + \text{anything})$; thin line, $\sigma(\nu_\ell N \rightarrow \ell^- + \text{anything})$; thick line, total (charged-current plus neutral-current) cross section.

R. Gandhi, C. Quigg, M. H. Reno and I. Sarcevic,
Neutrino interactions at ultrahigh energies,
Phys. Rev. D 58, 093009 (1998)
[hep-ph/9807264].

$\sigma(\bar{\nu}N)$ vs. E

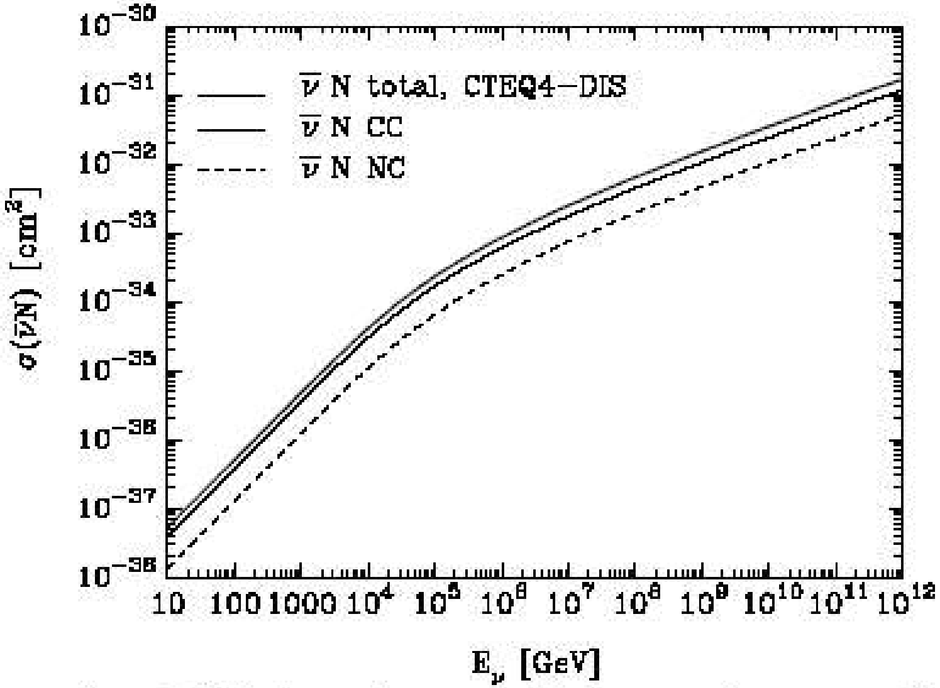


FIG. 3. Cross sections for $\bar{\nu}_\ell N$ interactions at high energies, according to the CTEQ4–DIS parton distributions: dashed line, $\sigma(\bar{\nu}_\ell N \to \bar{\nu}_\ell + \text{anything})$; thin line, $\sigma(\bar{\nu}_\ell N \to \ell^+ + \text{anything})$; thick line, total (charged-current plus neutral-current) cross section.

R. Gandhi, C. Quigg, M. H. Reno and I. Sarcevic,
Neutrino interactions at ultrahigh energies,
Phys. Rev. D 58, 093009 (1998)
[hep-ph/9807264].

Clarification on δ_{CP}

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{j>k} Re(J_{\alpha\beta jk}) \sin^2 \frac{\Delta m^2_{jk} L}{4E} + 2\sum_{j>k} Im(J_{\alpha\beta jk}) \sin \frac{\Delta m^2_{jk} L}{2E}$$

$$J_{\alpha\beta jk} \;=\; U_{\beta j} U^*_{\beta k} U^*_{\alpha j} U_{\alpha k}$$

$$\nu \;\to\; \bar{\nu} \qquad J_{\alpha\beta jk} \to J^*_{\alpha\beta jk}$$

$$Im(J_{\alpha\beta jk}) \;=\; J \sum_{\gamma,l} \epsilon_{\alpha\beta\gamma}\, \epsilon_{jkl}$$

Jarlskog determinant $\quad J = c_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \sin \delta$

$$P(\nu_e \to \nu_\mu) = P(\bar{\nu}_\mu \to \bar{\nu}_e) \;=$$

$$4c^2_{13}[\sin^2 \Delta_{23} s^2_{12} s^2_{13} s^2_{23} \;+\; c^2_{12}(\sin^2 \Delta_{13} s^2_{13} s^2_{23} + \sin^2 \Delta_{12} s^2_{12}(1 - (1 + s^2_{13}) s^2_{23}))]$$

CP-even $\quad - \;\frac{1}{4}|\tilde{J}| \cos \delta [\cos 2\Delta_{13} - \cos 2\Delta_{23} - 2\cos 2\theta_{12} \sin^2 \Delta_{12}]$

CP-odd $\quad + \;\frac{1}{4}|\tilde{J}| \sin \delta [\sin 2\Delta_{12} - \sin 2\Delta_{13} + \sin 2\Delta_{23}],$

Apollonio et al. hep-ph/0210192