Astrofizyka cząstek

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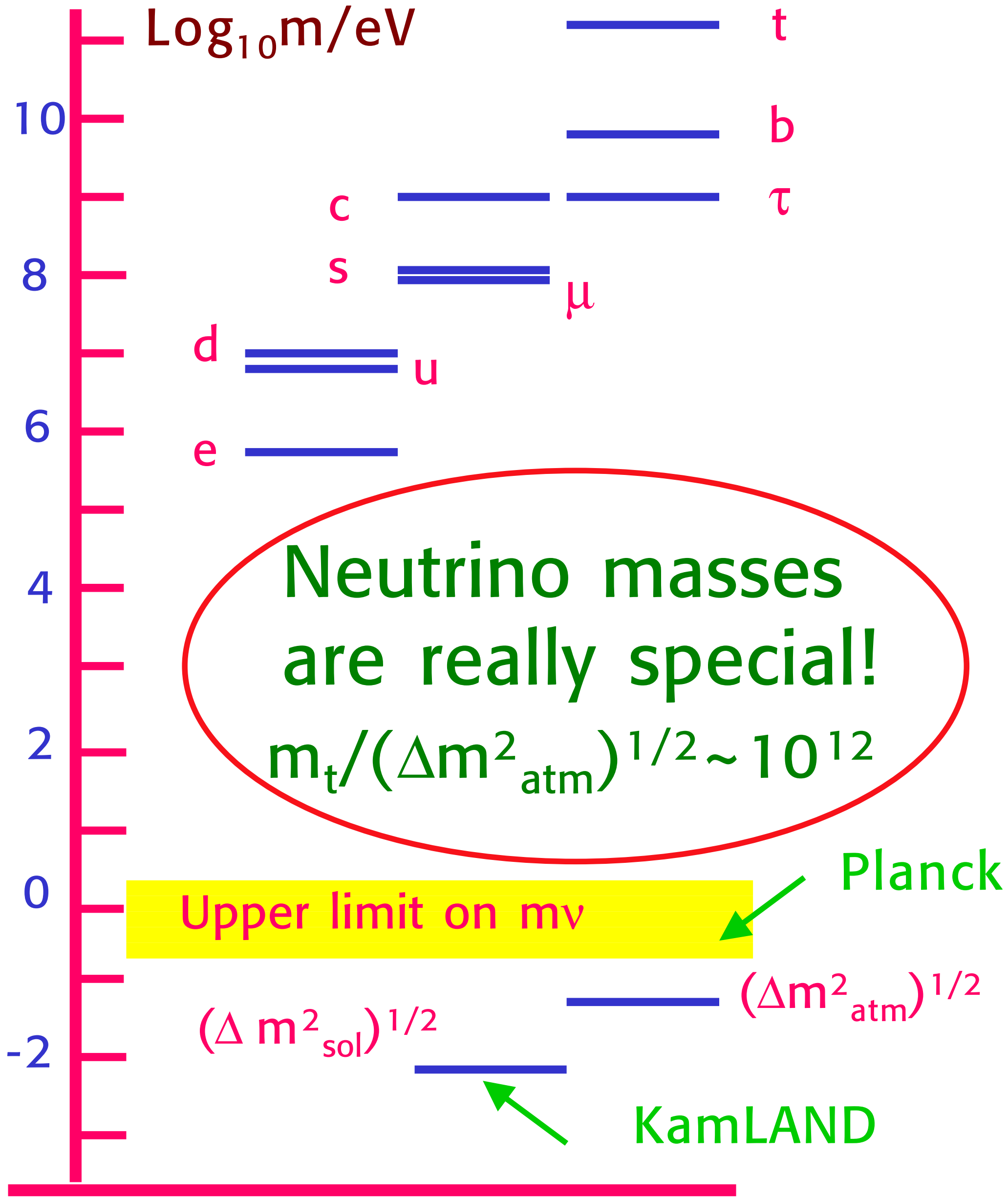
Zakład Cząstek i Oddziaływań Fundamentalnych IFD

Wykład X

- "Astronomia" neutrin



Neutrino masses are really special!

$m_t/(\Delta m^2_{atm})^{1/2} \sim 10^{12}$

Massless ν's?

- no ν_R
- L conserved

But ν_R can well exist and we really have no reason to expect that B and L are exactly conserved

Small ν masses?

- ν_R very heavy
- L not exactly cons.

The SM can be easily extended to include Majorana ν's

Neutrino Oscillations

- 1957: Bruno Pontecorvo proposed Neutrino Oscillations in analogy with $K^0 \leftrightarrows \bar{K}^0$ oscillations (Gell-Mann and Pais, 1955)

- Flavor Neutrinos: ν_e, ν_μ, ν_τ produced in Weak Interactions

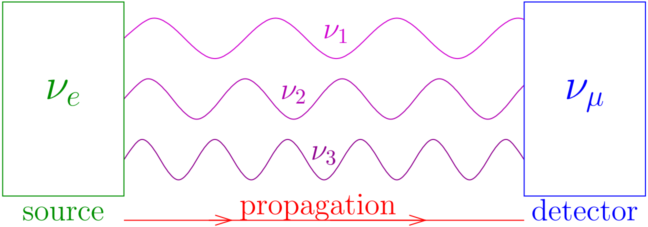
- Massive Neutrinos: ν_1, ν_2, ν_3 propagate from Source to Detector

- A Flavor Neutrino is a superposition of Massive Neutrinos

$$\begin{aligned}
|\nu_e\rangle &= U_{e1}\,|\nu_1\rangle + U_{e2}\,|\nu_2\rangle + U_{e3}\,|\nu_3\rangle \\
|\nu_\mu\rangle &= U_{\mu1}\,|\nu_1\rangle + U_{\mu2}\,|\nu_2\rangle + U_{\mu3}\,|\nu_3\rangle \\
|\nu_\tau\rangle &= U_{\tau1}\,|\nu_1\rangle + U_{\tau2}\,|\nu_2\rangle + U_{\tau3}\,|\nu_3\rangle
\end{aligned}$$

- U is the 3×3 Neutrino Mixing Matrix

$$|\nu(t=0)\rangle = |\nu_e\rangle = U_{e1}\,|\nu_1\rangle + U_{e2}\,|\nu_2\rangle + U_{e3}\,|\nu_3\rangle$$



$$|\nu(t>0)\rangle = U_{e1}\,e^{-iE_1 t}\,|\nu_1\rangle + U_{e2}\,e^{-iE_2 t}\,|\nu_2\rangle + U_{e3}\,e^{-iE_3 t}\,|\nu_3\rangle \neq |\nu_e\rangle$$

$$E_k^2 = p^2 + m_k^2$$

at the detector there is a probability > 0 to see the neutrino as a ν_μ

Neutrino Oscillations are Flavor Transitions $\propto \sin^2\left(\frac{\Delta m_{kj}^2 L}{4E}\right)^2$

$$\begin{array}{cccc} \nu_e \to \nu_\mu & \nu_e \to \nu_\tau & \nu_\mu \to \nu_e & \nu_\mu \to \nu_\tau \\ \bar\nu_e \to \bar\nu_\mu & \bar\nu_e \to \bar\nu_\tau & \bar\nu_\mu \to \bar\nu_e & \bar\nu_\mu \to \bar\nu_\tau \end{array}$$

transition probabilities depend on U and $\Delta m_{kj}^2 \equiv m_k^2 - m_j^2$

Experimental Evidences of Neutrino Oscillations

Solar
$\nu_e \to \nu_\mu, \nu_\tau$

(SNO, BOREXino
Super-Kamiokande
GALLEX/GNO, SAGE
Homestake, Kamiokande)

VLBL Reactor
$\bar{\nu}_e$ disappearance

(KamLAND)

$\to$

$\Delta m^2_{\text{S}} \simeq 7.6 \times 10^{-5}\,\text{eV}^2$

$\sin^2 \vartheta_{\text{S}} \simeq 0.30$

Atmospheric
$\nu_\mu \to \nu_\tau$

(Super-Kamiokande
Kamiokande, IMB
MACRO, Soudan-2)

LBL Accelerator
ν_μ disappearance

(K2K, MINOS, T2K)

LBL Accelerator
$\nu_\mu \to \nu_\tau$

(Opera)

$\to$

$\Delta m^2_{\text{A}} \simeq 2.4 \times 10^{-3}\,\text{eV}^2$

$\sin^2 \vartheta_{\text{A}} \simeq 0.50$

LBL Accelerator
$\nu_\mu \to \nu_e$

(T2K, MINOS)

LBL Reactor
$\bar{\nu}_e$ disappearance

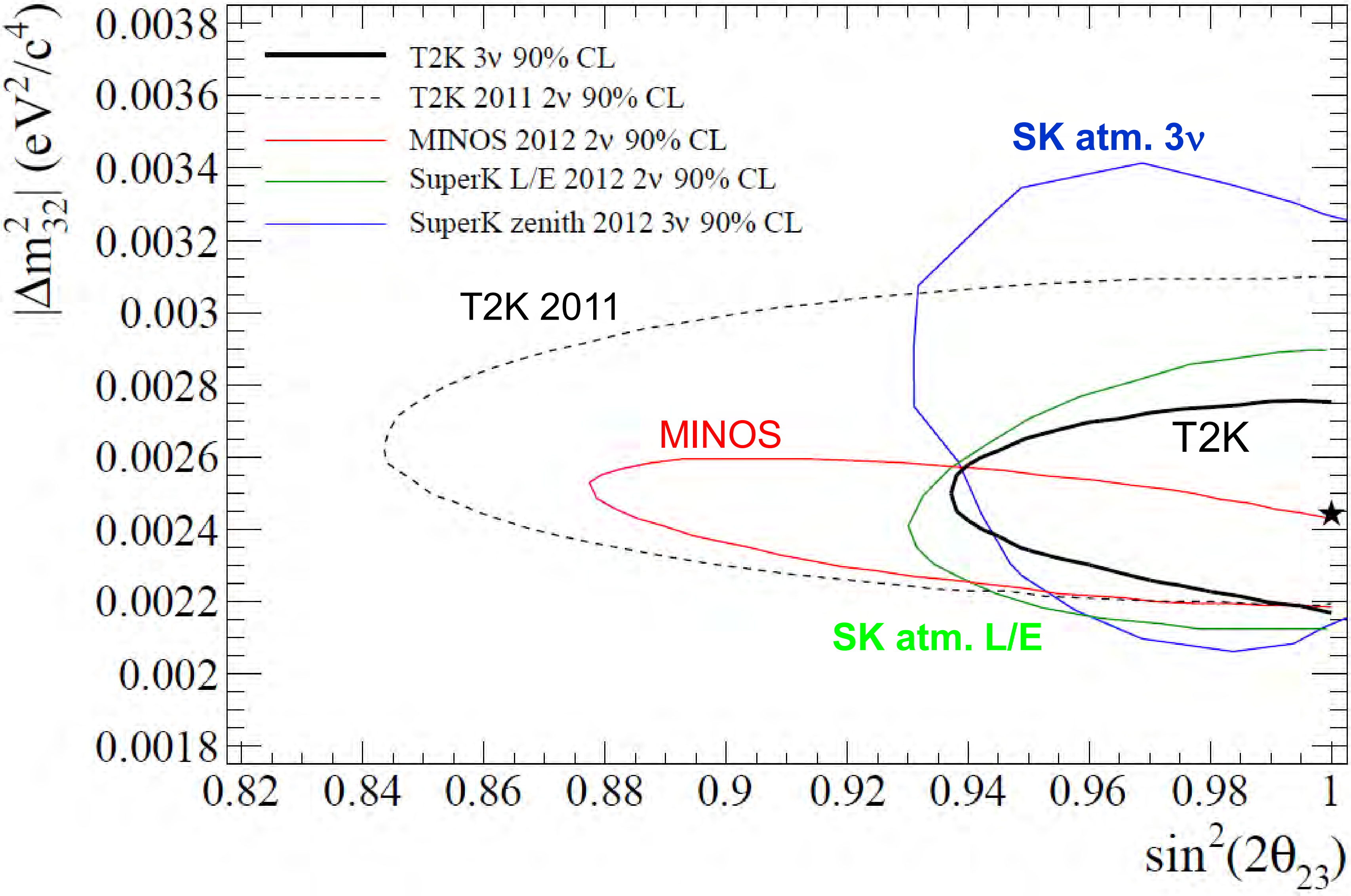
(Daya Bay, RENO
Double Chooz)

$\to$

Δm^2_{A}

$\sin^2 \vartheta_{13} \simeq 0.023$

$\theta_{23} - |\Delta m_{32}^2|$: SK atm. and accelerators

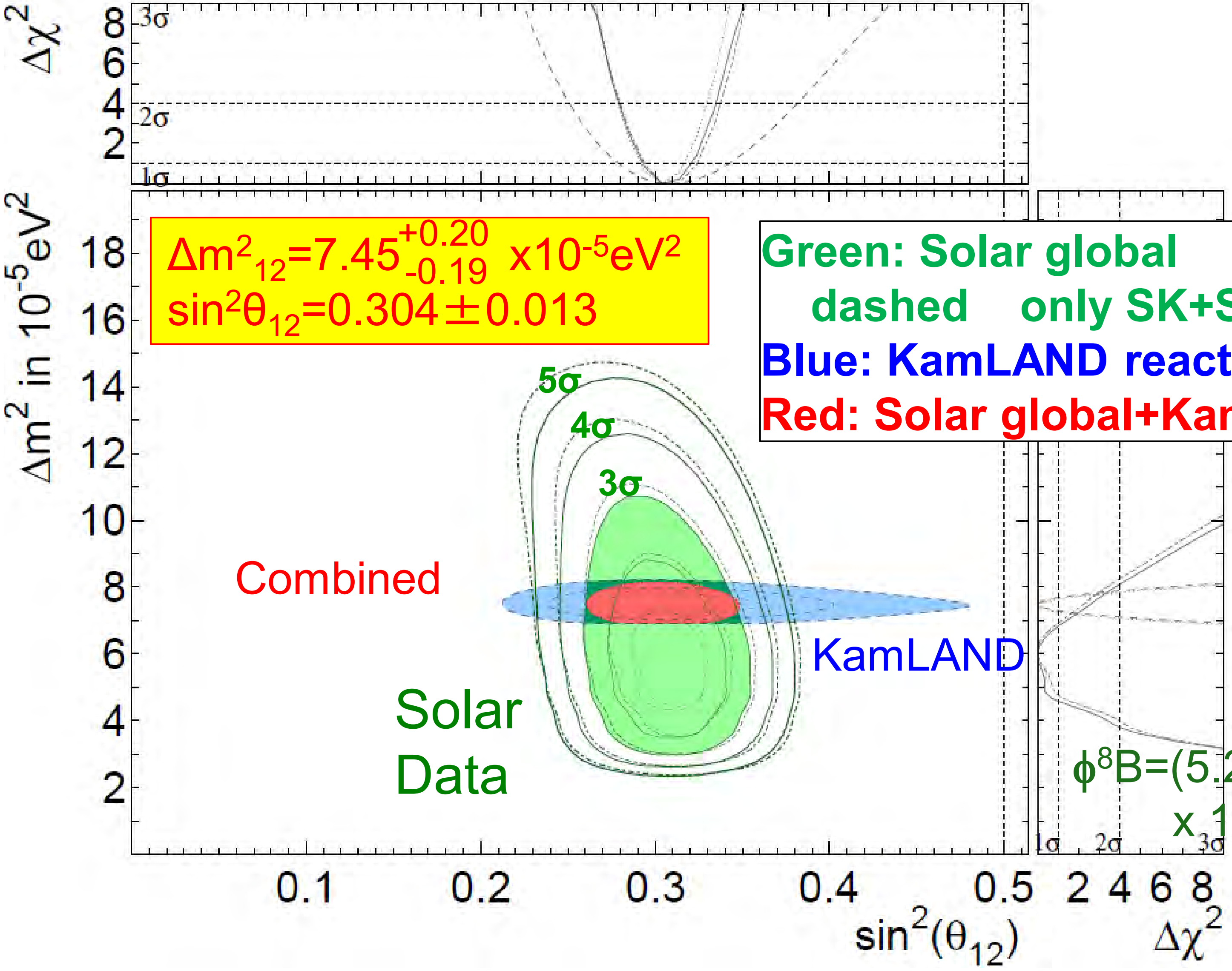


Future: T2K will reach accuracy of $\delta(\sin^2 2\theta_{23})=0.01$ and $\delta(\Delta m^2_{32})=0.0001 eV^2$.

$\theta_{12} - \Delta m_{21}^2$: solar and KamLAND-reactor

H.Sekiya (ID:48)

NU-EX03

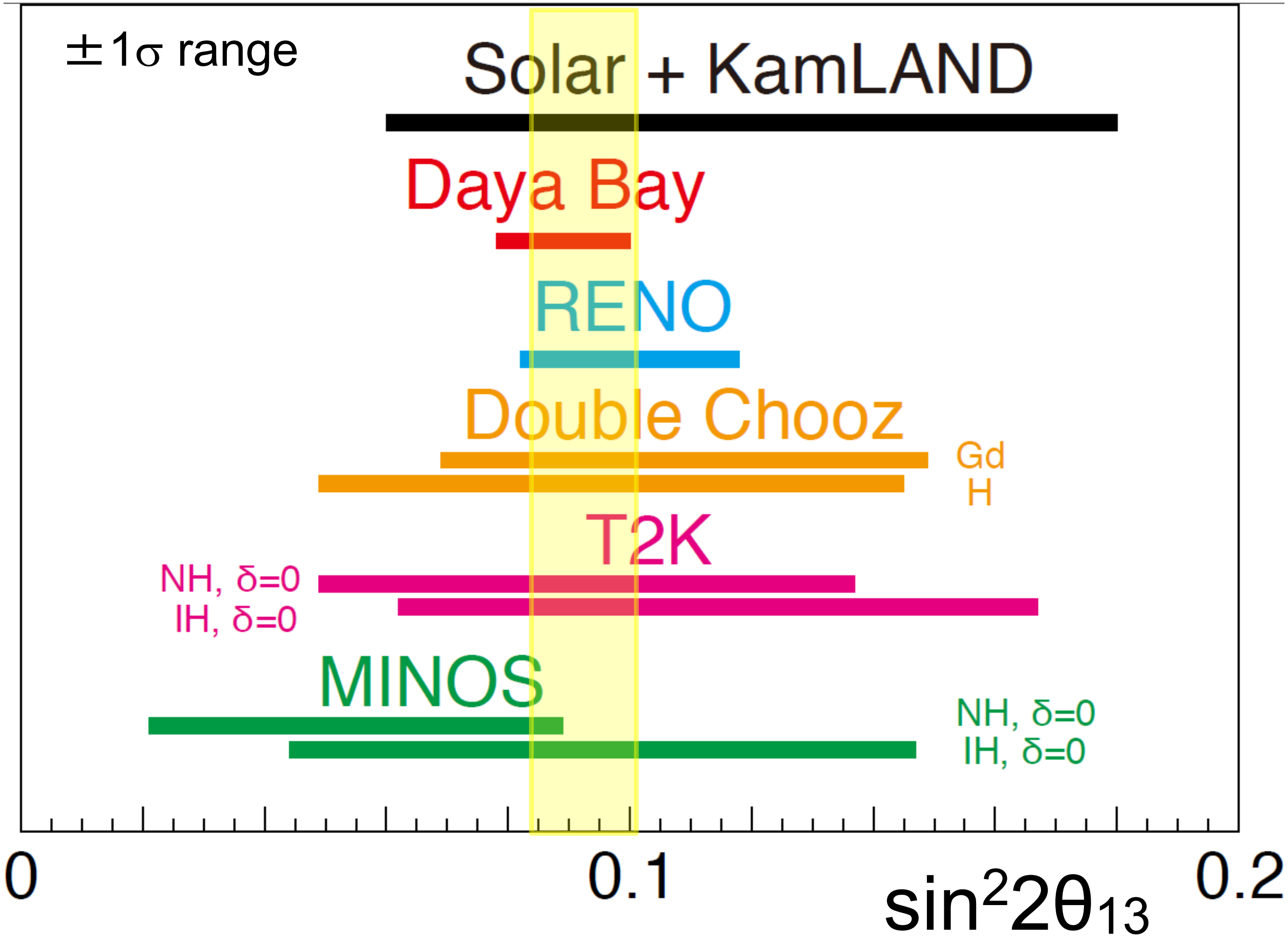


$\Delta m^2_{12}=7.45^{+0.20}_{-0.19}\ \mathrm{x}10^{-5}\mathrm{eV}^2$
$\sin^2\theta_{12}=0.304\pm0.013$

Green: Solar global
dashed only SK+SNO
Blue: KamLAND reactor
Red: Solar global+KamLAND

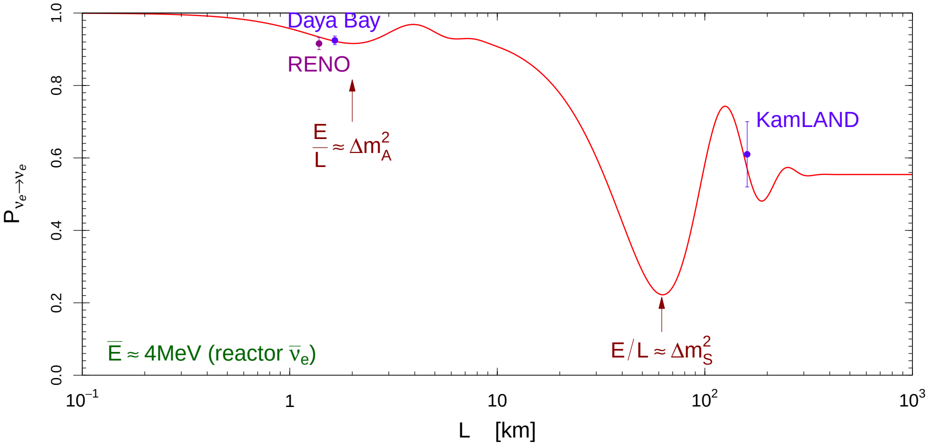
$\phi^8\mathrm{B}=(5.25\pm0.20)$
$\mathrm{x}\ 10^6/(\mathrm{cm}^2\cdot\mathrm{sec})$

Summary of θ13 measurements



All results are consistent.

Reactor combine: $\sin^2 2\theta_{13} = 0.093 \pm 0.009$



$P_{\nu_e \to \nu_e}$
1.0
0.8
0.6
0.4
0.2
0.0
Daya Bay
RENO
$\frac{E}{L} \approx \Delta m^2_A$
KamLAND
$E/L \approx \Delta m^2_S$
$\overline{E} \approx 4\mathrm{MeV}$ (reactor $\overline{\nu}_e$)
10^{-1}
1
10
10^2
10^3
L [km]

Experimental Indications of Sterile Neutrinos

- LSND: Accelerator $\bar{\nu}_{\mu} \to \bar{\nu}_{e}$

$$L \simeq 30\,\text{m} \qquad E \simeq 50\,\text{MeV}$$

3.8σ excess $\Delta m^2 \gtrsim 0.2\,\text{eV}^2$ $(\gg \Delta m^2_{\text{A}} \gg \Delta m^2_{\text{S}})$ [PRD 64 (2001) 112007]

- Reactor Electron Antineutrino Anomaly: $\bar{\nu}_{e} \to \bar{\nu}_{e}$

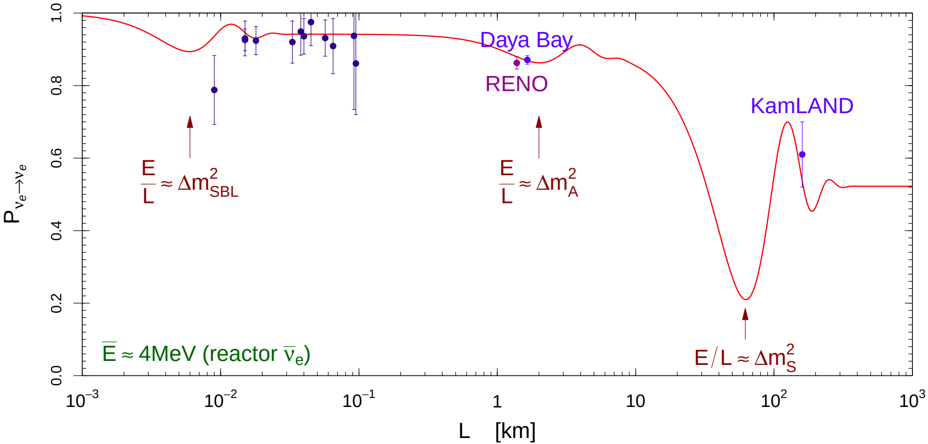
$$L \simeq 10 - 100\,\text{m} \qquad E \simeq 4\,\text{MeV}$$

2.8σ deficit $\Delta m^2 \gtrsim 0.5\,\text{eV}^2$ [Mention et al, PRD 83 (2011) 073006]

- Gallium Anomaly: $\nu_{e} \to \nu_{e}$

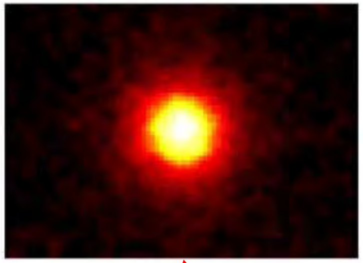
$$L \simeq 1\,\text{m} \qquad E \simeq 1\,\text{MeV}$$

2.9σ deficit $\Delta m^2 \gtrsim 1\,\text{eV}^2$ [SAGE, PRC 73 (2006) 045805]


$P_{\nu_e \to \nu_e}$
1.0
0.8
0.6
0.4
0.2
0.0
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
10^{3}
L [km]
Daya Bay
RENO
KamLAND
$\frac{E}{L} \approx \Delta m^2_{SBL}$
$\frac{E}{L} \approx \Delta m^2_{A}$
$E/L \approx \Delta m^2_{S}$
$\overline{E} \approx 4$MeV (reactor $\overline{\nu}_e$)

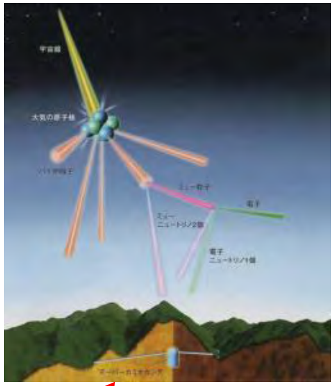
Physics of wide energy range

Solar neutrinos

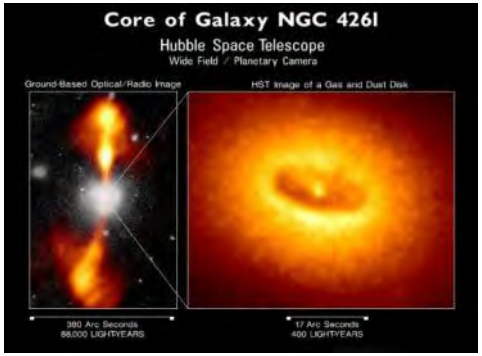


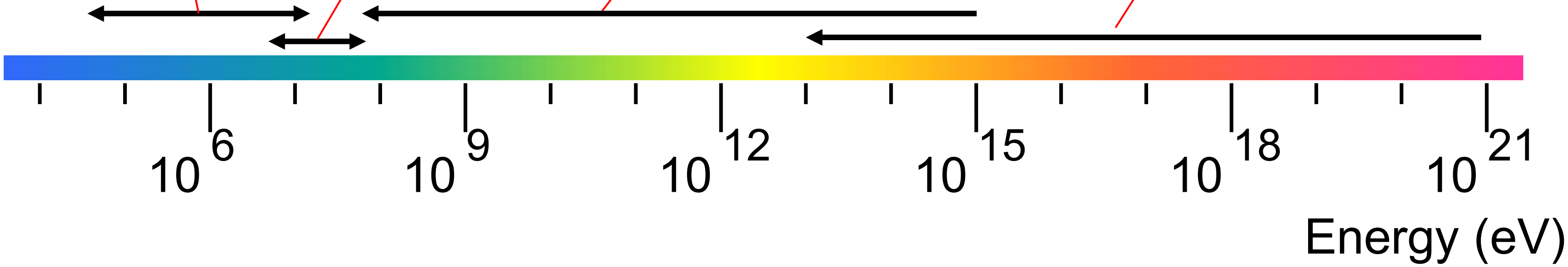
Supernova burst

Atmospheric neutrinos



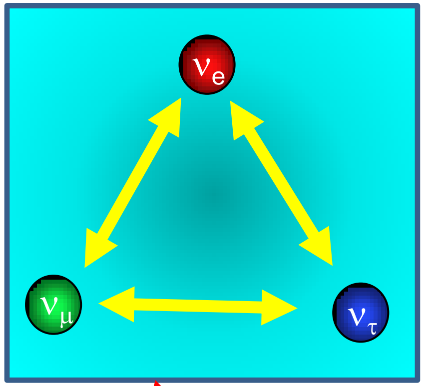
High energy neutrino astronomy



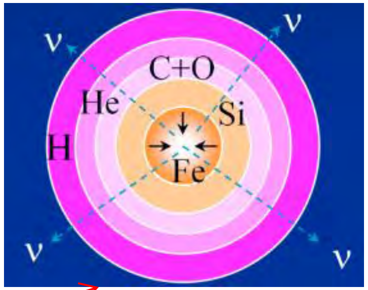


Many physics topics

Neutrino oscillations

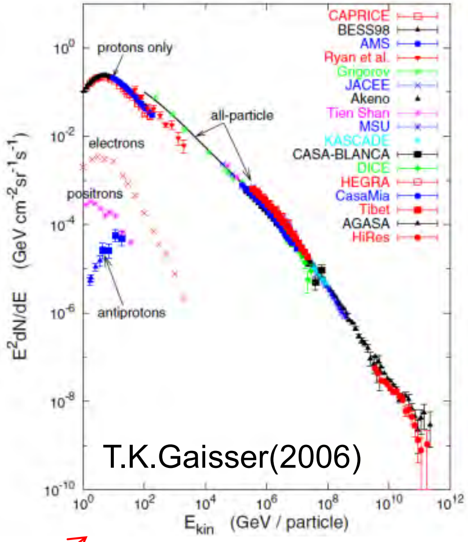


Supernova mechanism

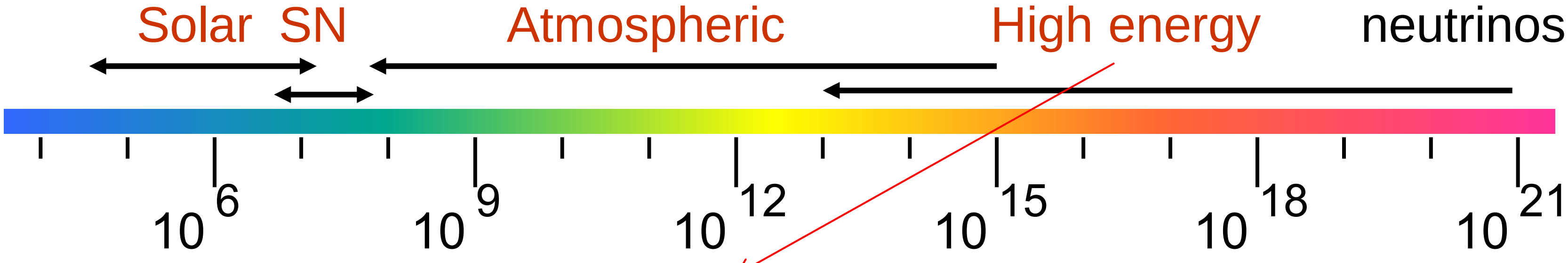


Origin of cosmic ray

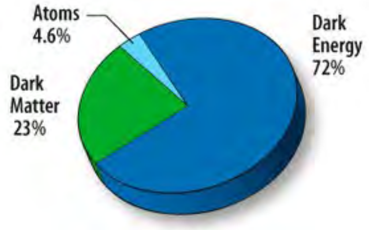
Acceleration mechanism



T.K.Gaisser(2006)



Energy (eV)



Dark matter

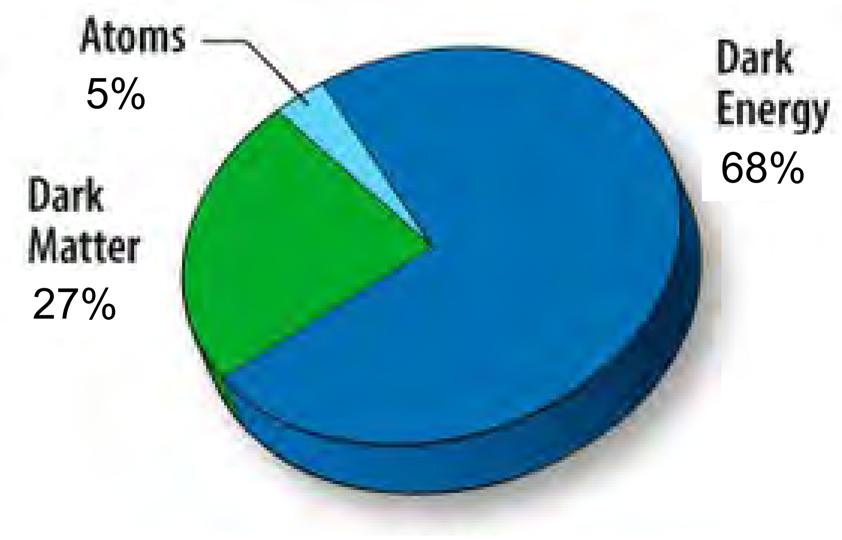
The concordance flat ΛCDM model...

The simplest model consistent with **present observations**.

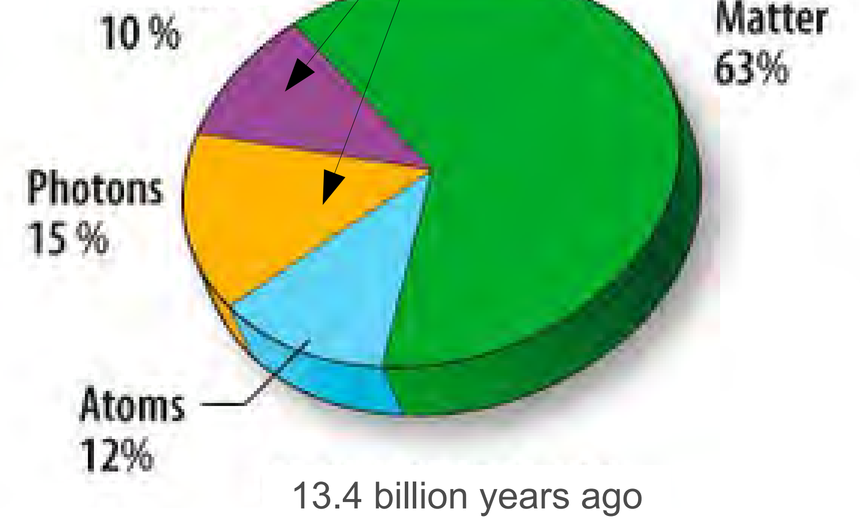
Min. value from $\sum m_\nu = 0.06\,\mathrm{eV}$
oscillations experiments

(Nearly)
Massless
Neutrinos
(3 families)

ν-to-γ energy density
ratio fixed by SM physics



Composition today



13.4 billion years ago
(at photon decoupling)

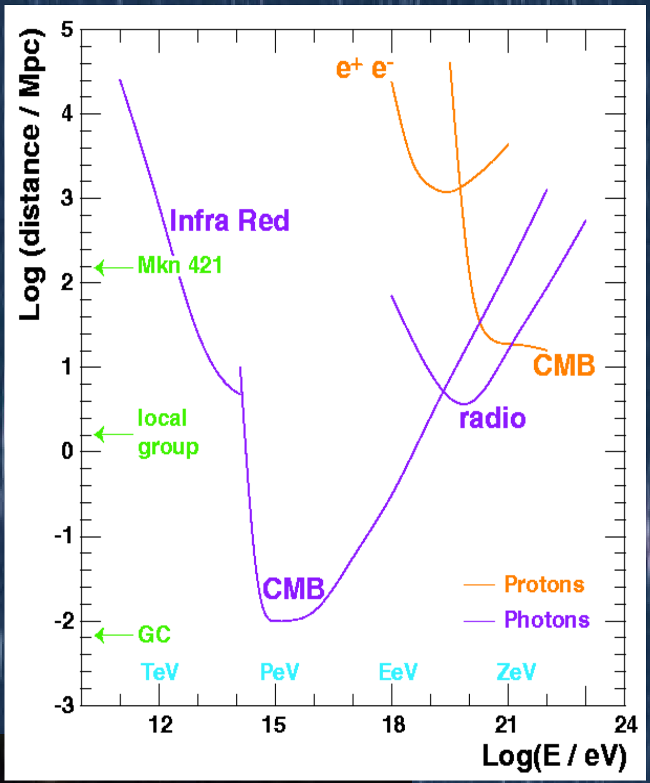
Plus flat spatial geometry+initial conditions
from single-field inflation

Neutrino astronomy

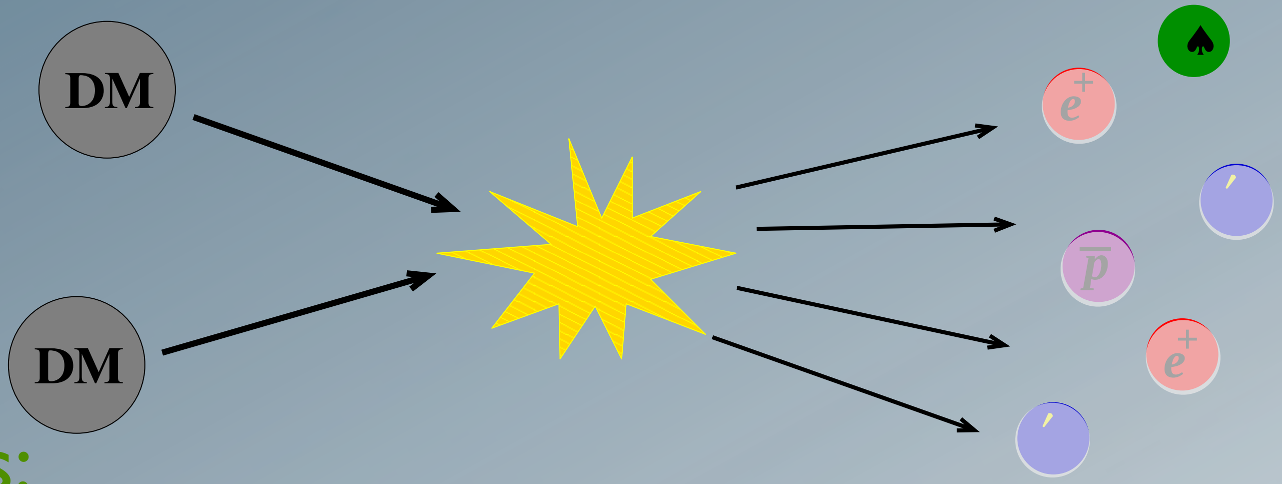
- Advantages w.r.t. other messengers:
  - Photons: interact with CMB and matter
  - Protons: interact with CMB and are deflected by magnetic fields

- Drawback: large detectors (~GTon) are needed.

Photon and proton mean free range path



Indirect DM searches



Neutrinos:

- Unperturbed propagation like for photons
- But signal significance (for the same target) usually considerably worse
- New feature: signals from the center of sun or earth!

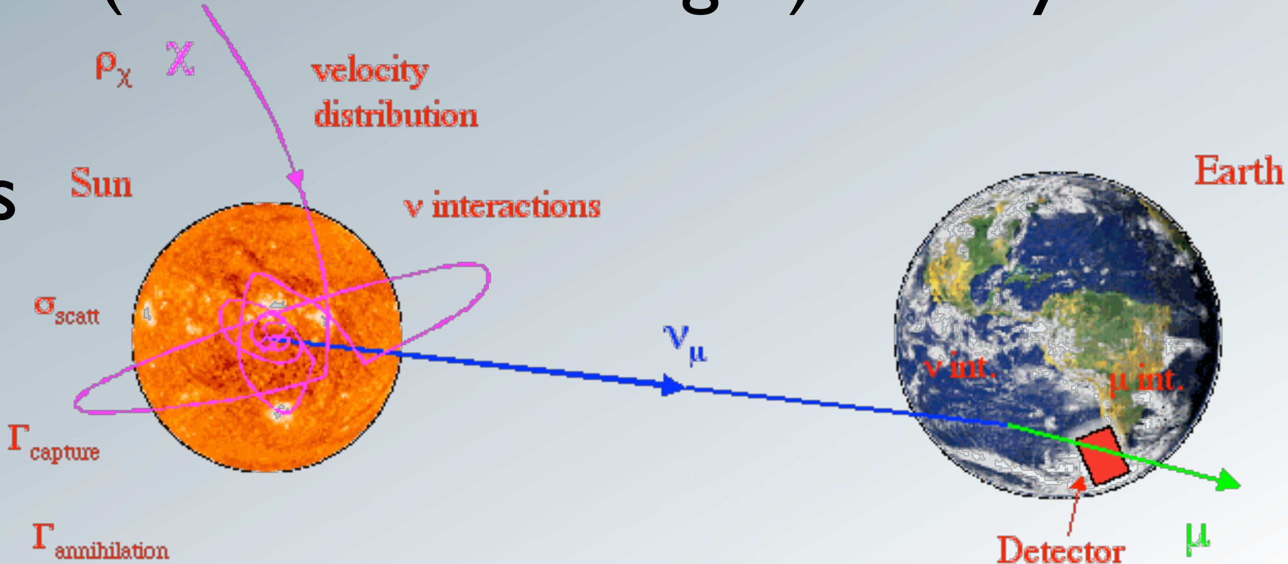
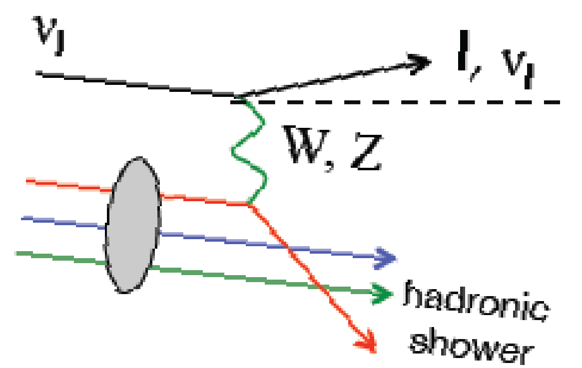


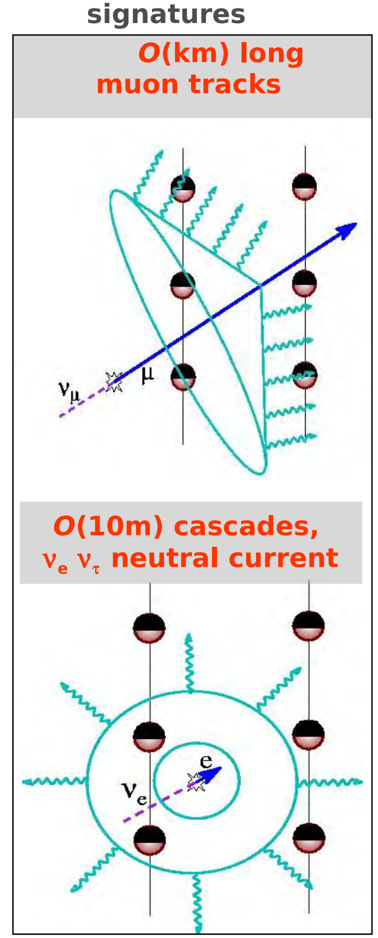
Fig. from J.Edsjö

Detection principle



- Array of optical modules in transparent medium (ice/water) to detect Cherenkov light from relativistic secondaries
  (mostly sensitive to muons because they have the longest tracks)
- opening angle: $\Theta_{\mu\nu} \approx 0.7^\circ \cdot (E_\nu / \mathrm{TeV})^{-0.7}$
  ⇨ possible to do neutrino astronomy!
- tiny *x*-sections & fluxes: *need HUGE volumes!*
- background muons:
  - down-going: atmospheric neutrinos
  - up-going: also induced by cosmic rays
    (hitting the atmosphere the far side of the earth)

  look for excesses in any given direction

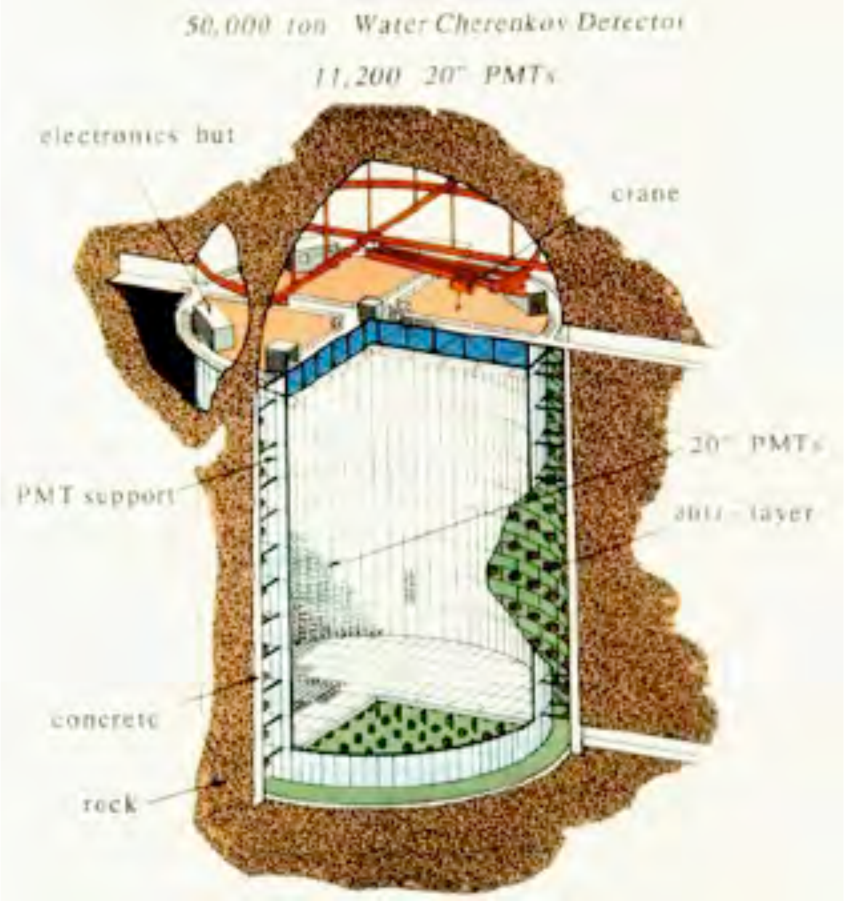


Introduction to neutrino experiments

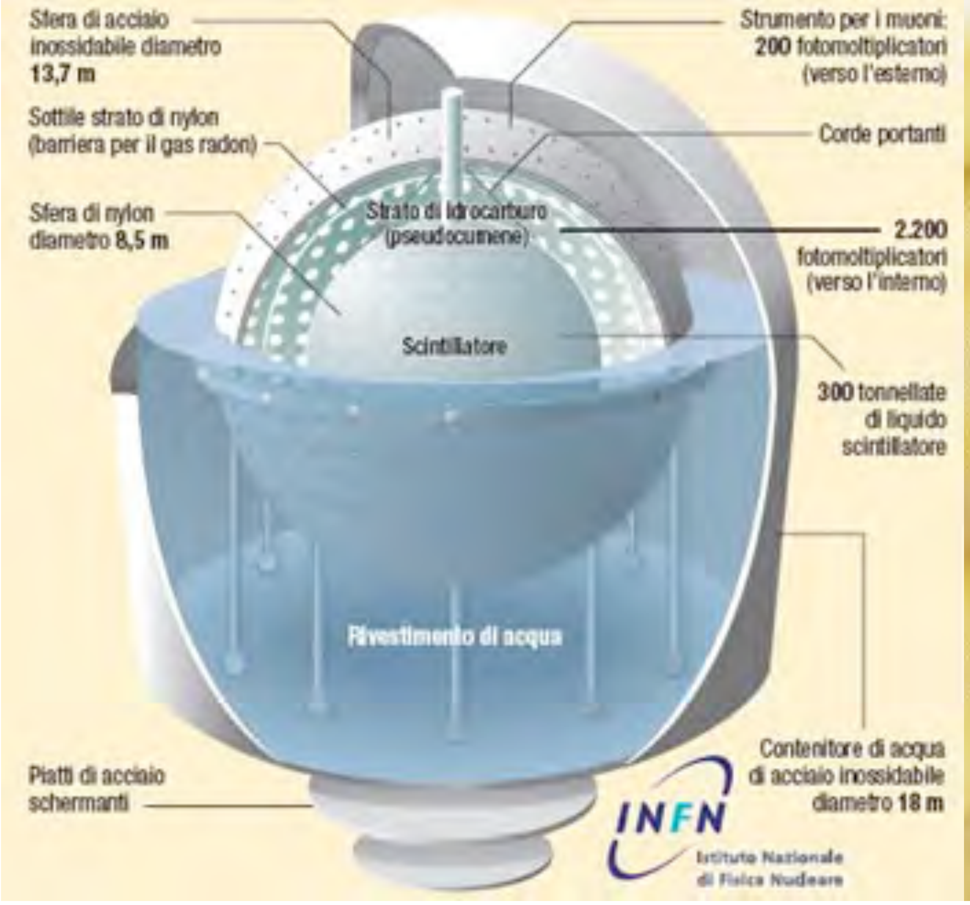
Low (**< 10 GeV**) Energy Experiments are installed in underground facilities:

- Neutrinos from SN Core Collapse

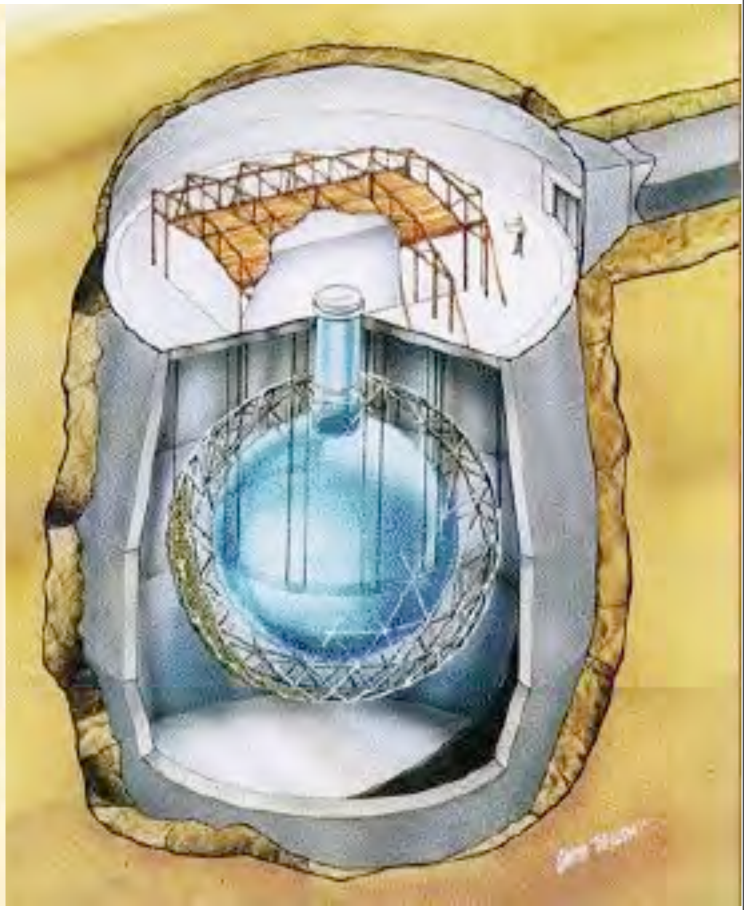
- Neutrinos from Sun



SuperKamiokande



Borexino

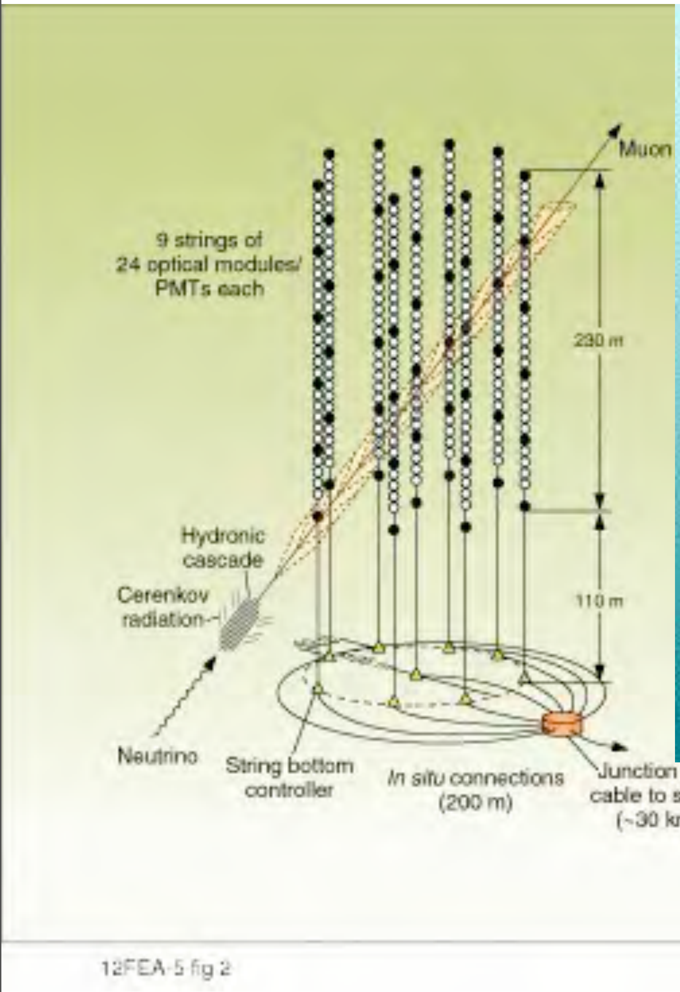


SNO

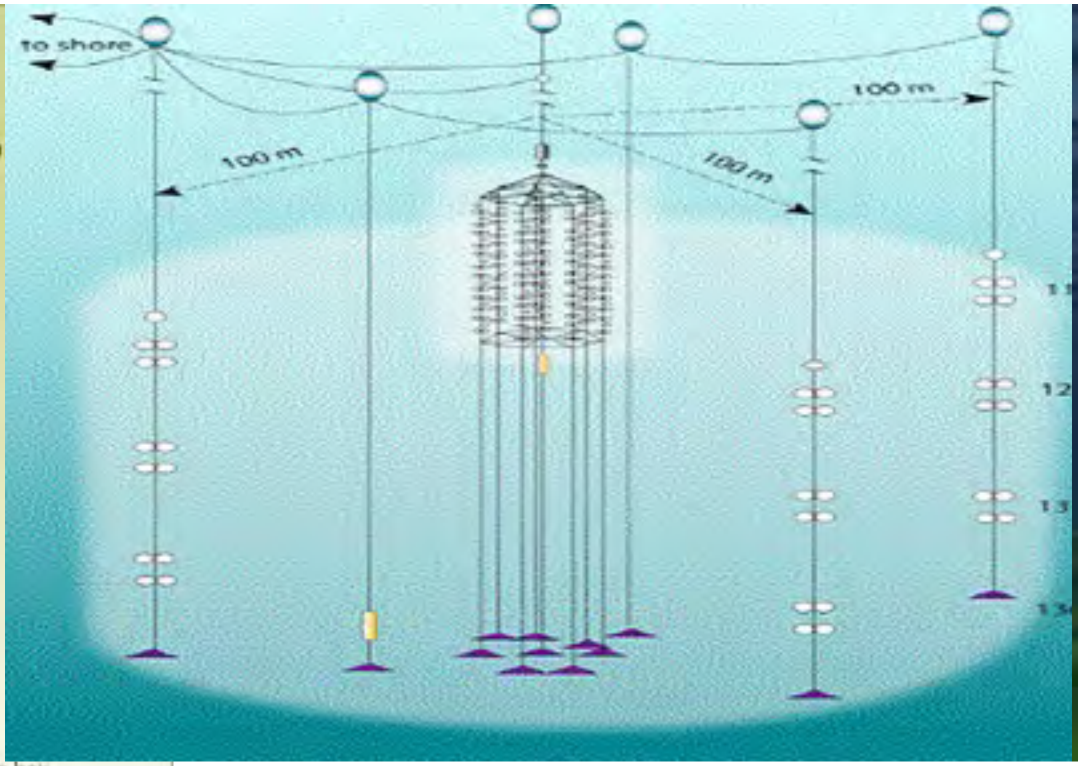
Discovery of neutrino oscillation, SN 1987A

Introduction to neutrino experiments

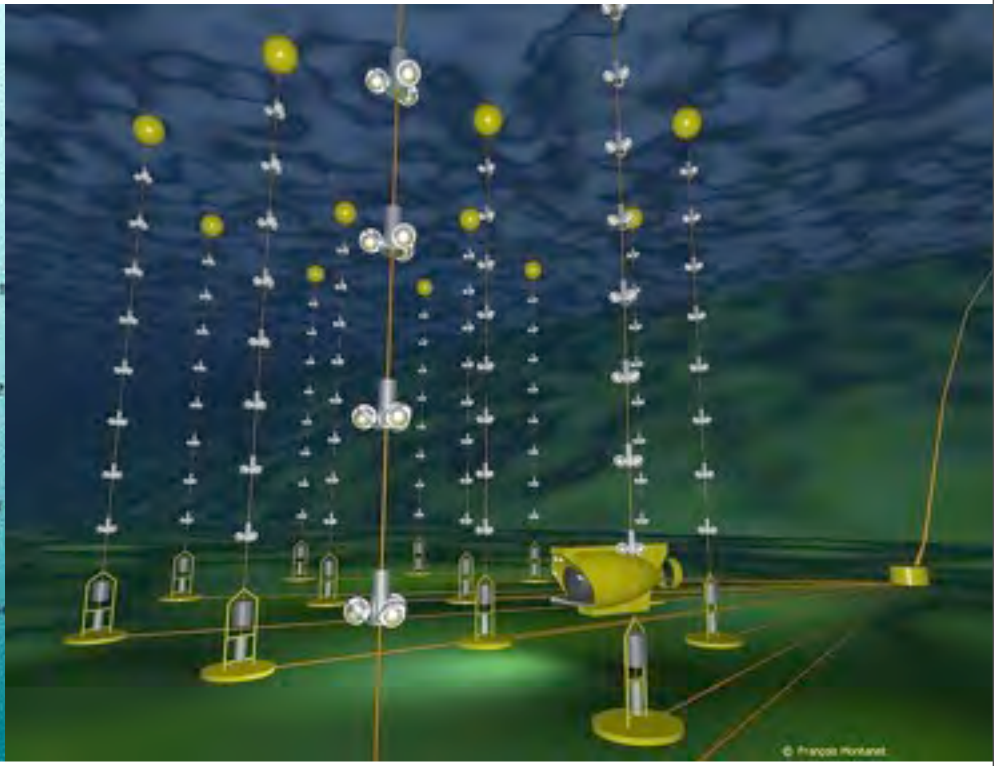
High (**>100 GeV**) Energy Experiments are installed in natural medium:
Option 1: WATER



DUMAND (never realized)



Baikal Neutrino Telescope



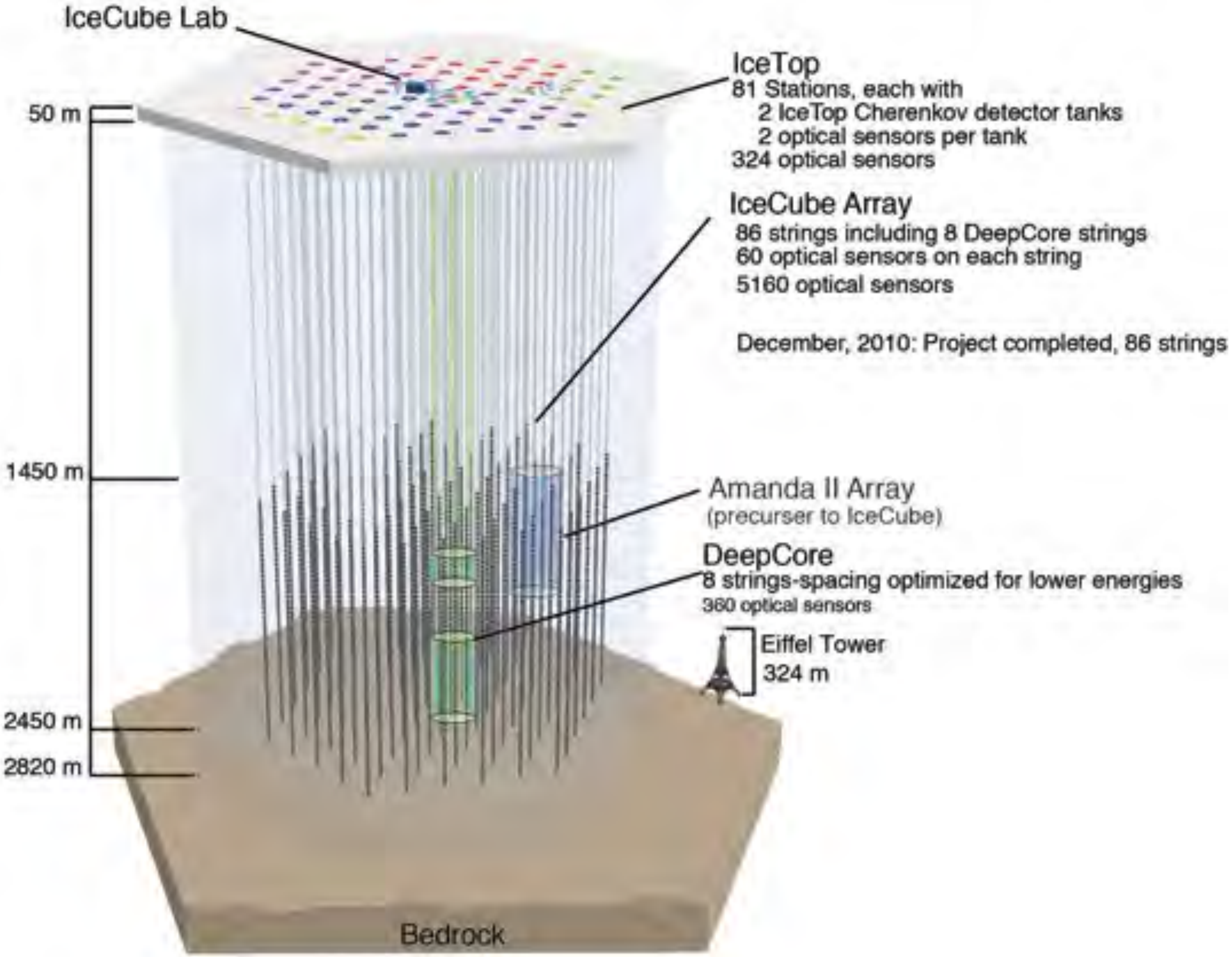
Antares

Introduction to neutrino experiments

High (**>100GeV**) Energy Experiments are installed in natural medium:
Option2: Ice @ South Pole

Extension at lower energies
(**~100 GeV - ~10 GeV**):
DeepCore

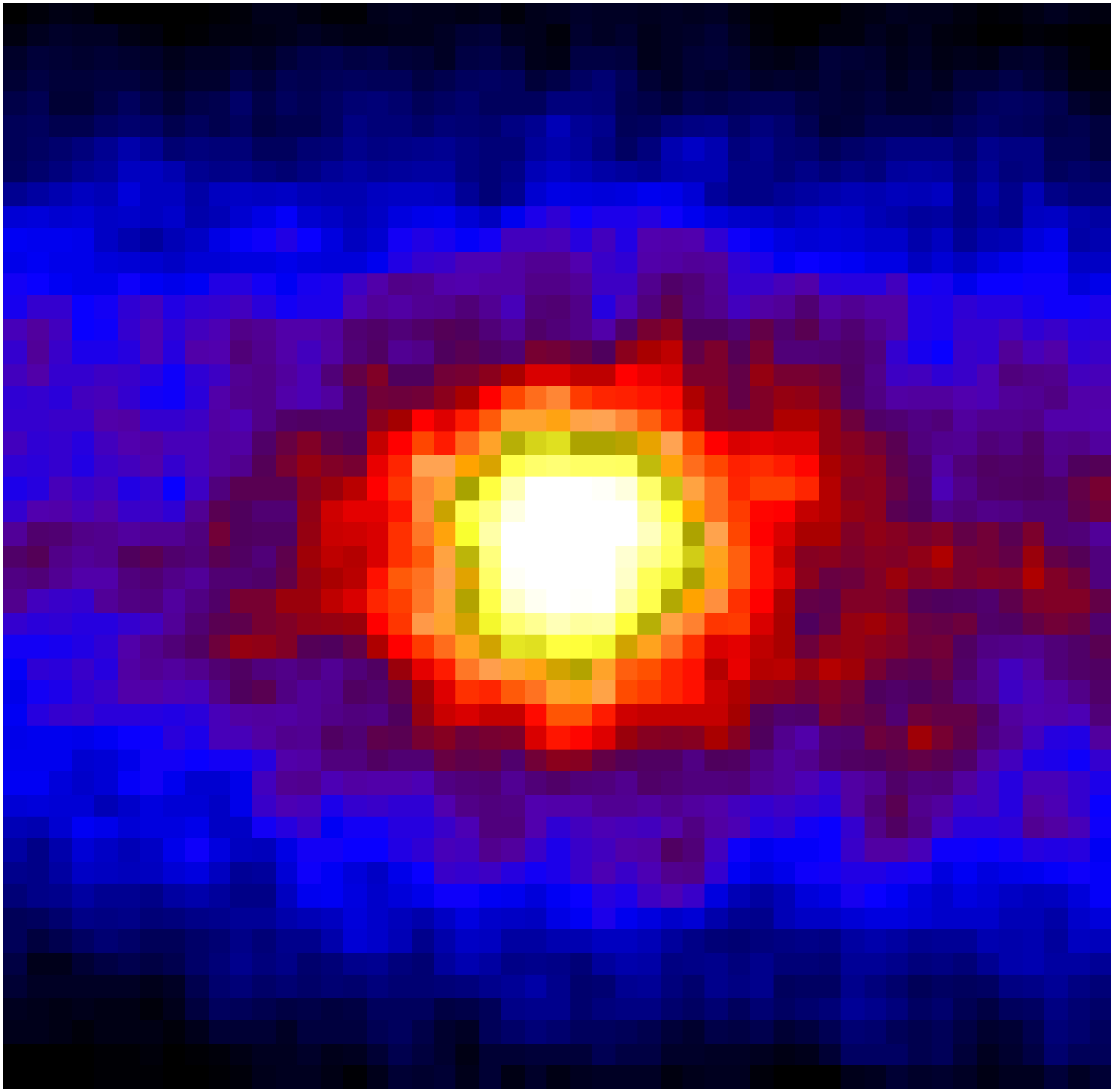
AMANDA (decommissioned),
IceCube (IceTop, "in-ice",
DeepCore)



Super-Kamiokande

“Zdjęcie” Słońca
w “świetle” neutrin

rzeczywisty rozmiar
Słońca $\sim \frac{1}{2}$ pixla



Neutrina słoneczne

Widmo energii

Widmo energii neutrin elektronowych produkowanych w reakcjach jądrowych na słońcu ⇒

Strumień neutrin o energiach poniżej kilku MeV może być zmierzony metodami radiochemicznymi: mierzymy produkcję powstających izotopów:

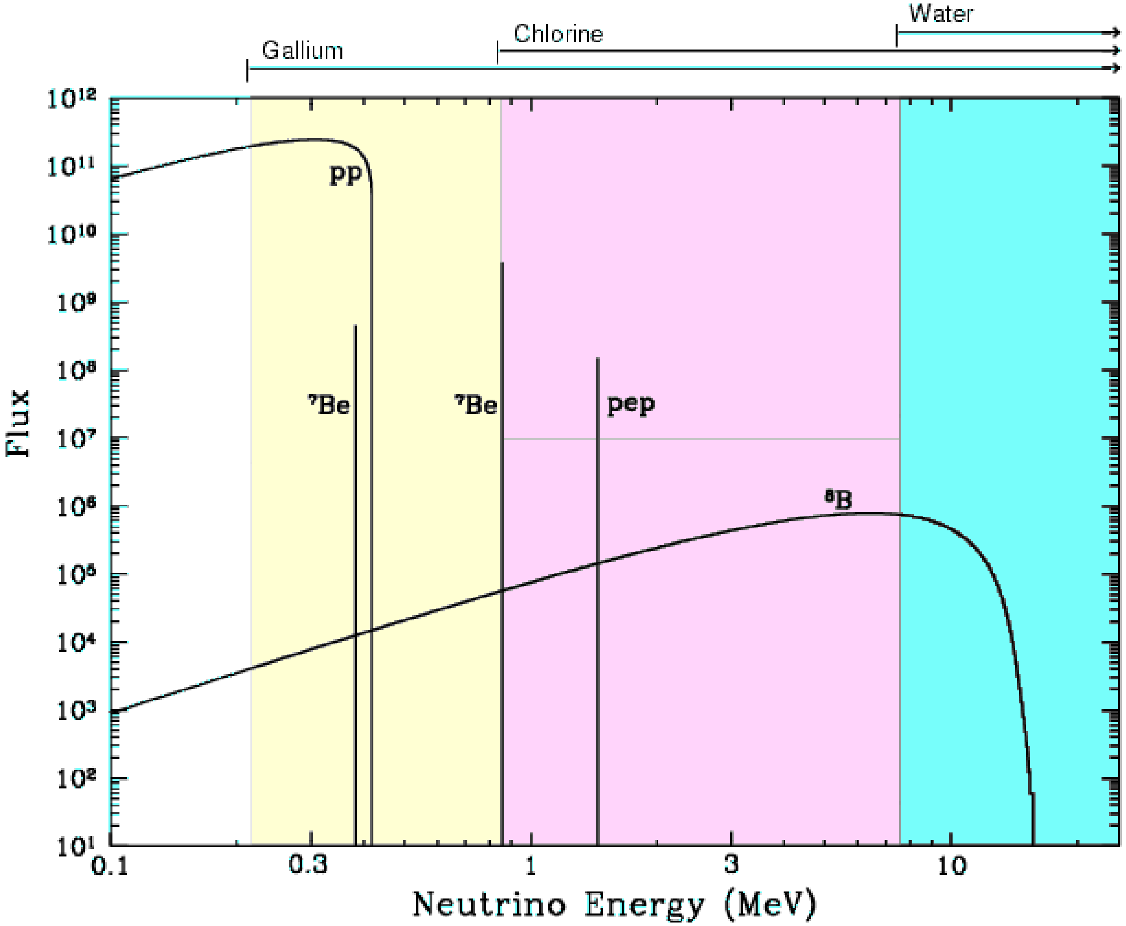
$$\nu_e + Cl \rightarrow Ar + e^-$$

(eksperyment Homestake)

$$\nu_e + Ga \rightarrow Gr + e^-$$

(SAGE, GALLEX, GNO)

Tylko neutrina elektronowe !



Ga Cl woda

Neutrina

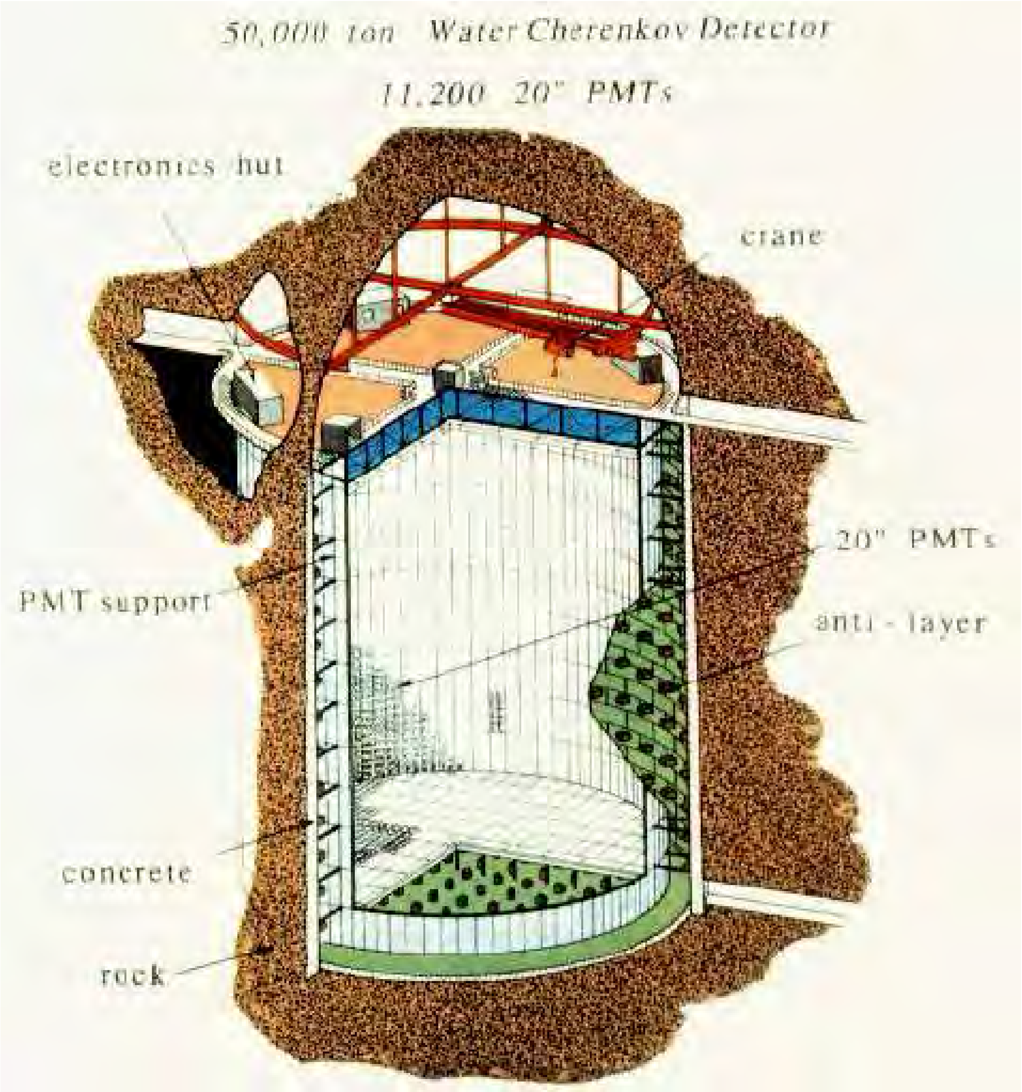
Eksperyment Super-Kamiokande

Japonia, w starej kopalni, 1 km pod górą Kamioka, komora o wysokości 40 m i średnicy 40 m, wypełniona wodą

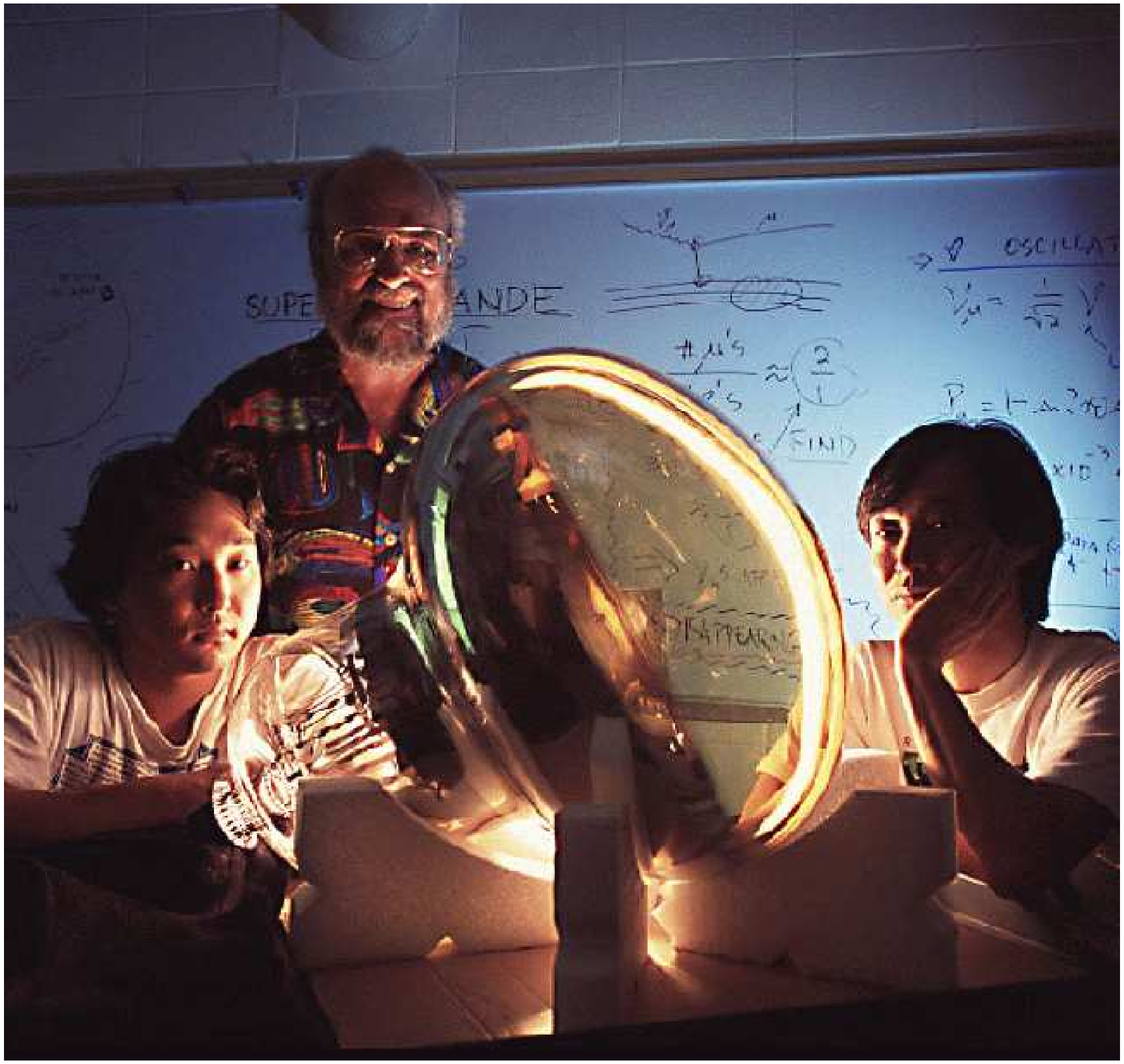
11’000 fotopowielaczy (50 cm średnicy!) rejestruje przechodzące cząstki

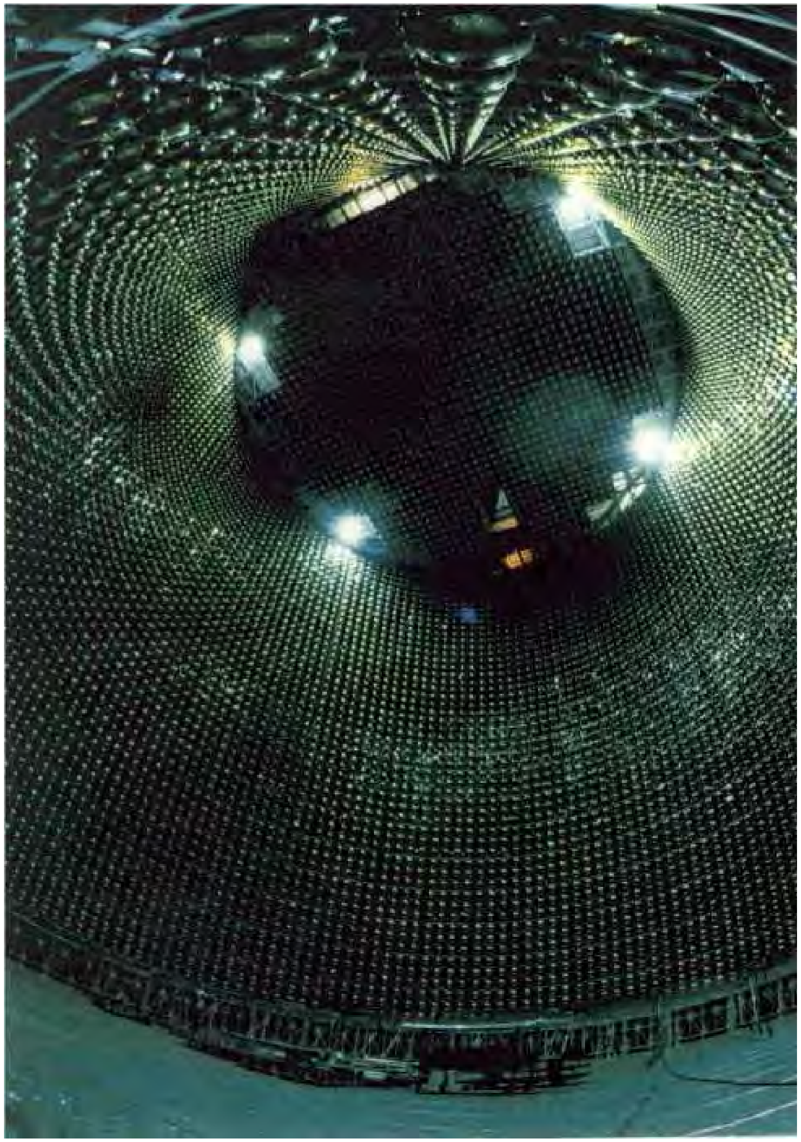
rejestrowane jest
promieniowanie Czerenkowa

Jak można mierzyć tak małe sygnały ($\sim 5 MeV$) w tak ogromnym detektorze?



Super-Kamiokande





Napełnianie

Super-Kamiokande

Tło

Mimo ogromnej masy detektora oczekiwano jedyni około 30 przypadków oddziaływań neutrin słonecznych na dobę.

Przypadki skrajnie niskich energii (rzędu 10 MeV) - konieczność redukcji tła.

Główne tło: naturalna promieniotwórczość.
Stężenie radonu w powietrzu w kopalnie $\sim 3000 Bq/m^3$

- ⇒ hermetyczne drzwi, intensywna wentylacja powietrzem zewnętrznym
- ⇒ cała komora wyłożona spejcalną platikową osłoną zabezpieczającą przed przenikanie radonu ze skał
- ⇒ hermetyczny zbiornik, dopełniony specjalnie oczyszczonym powietrzem ($3 mBq/m^3$) pod ciśnieniem wyższym od atmosferycznego
- ⇒ intensywne filtrowanie wody (ok. 35 t/h, czyli cały detektor w ok. 2 miesiące)

Super-Kamiokande

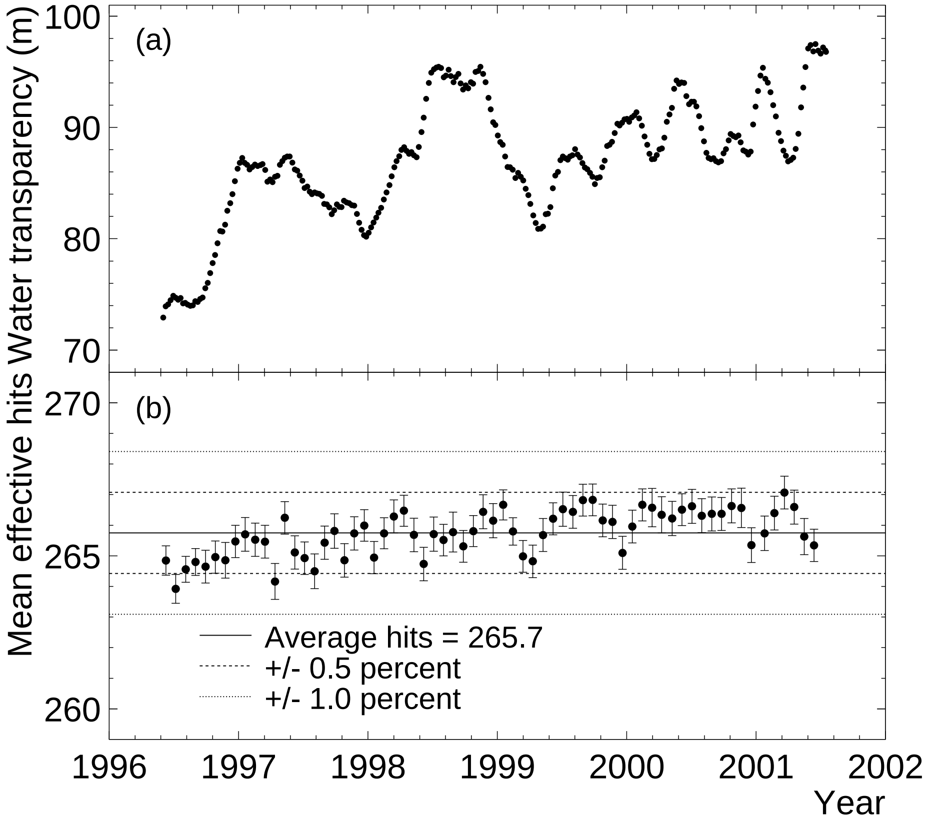
Kalibracja

Fotony przebiegają w wodzie do 60 m - atenuacja światła musi być dokładnie znana i monitorowana.

Można ją wyznaczyć z obserwacji sygnału z rozpadu zatrzymujących się mionów.

Około 1500 "kalibracyjnych" rozpadów dziennie.

Wystarcza do bardzo dokładnego monitorowania zmian w skali tygodni.



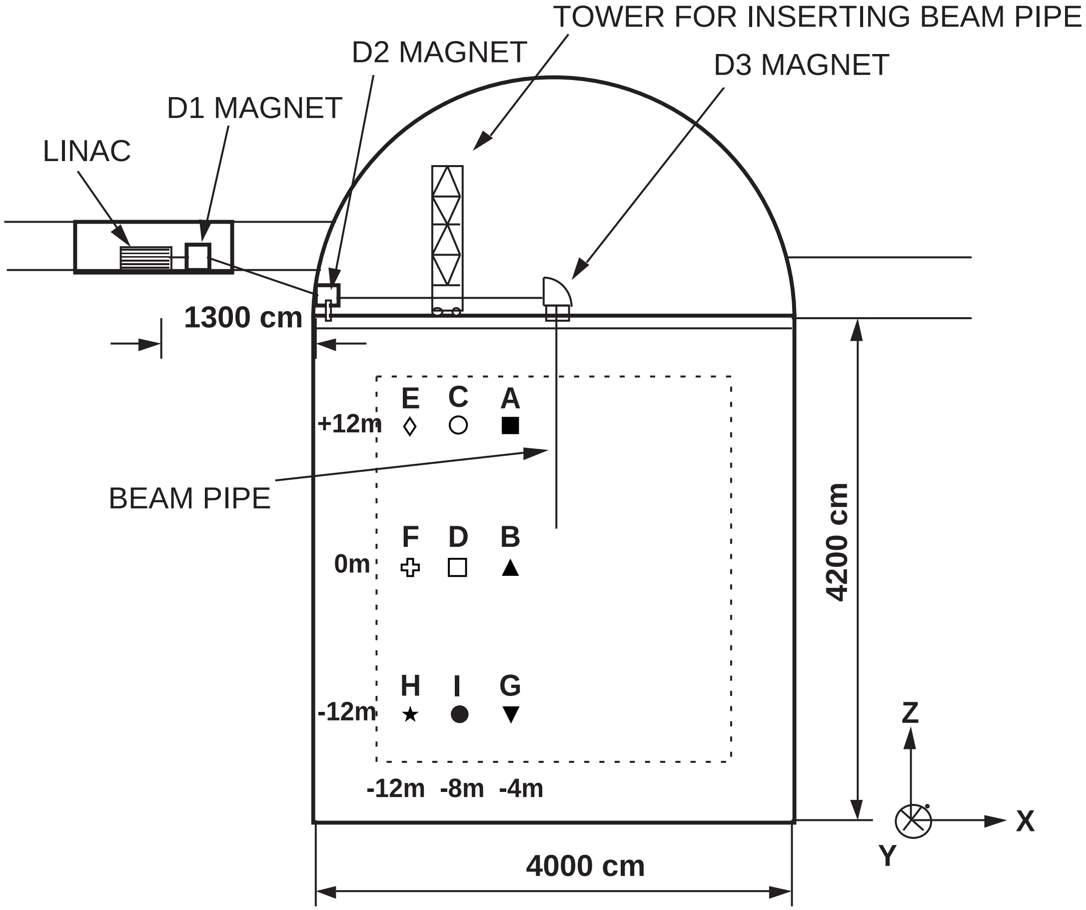
Super-Kamiokande

Kalibracja

Kalibracja energetyczna: kluczowa przy niskich energiach.

Główna metoda:
własny akcelerator (!) 5-16 MeV
(zakres energii mierzonych neutrin)

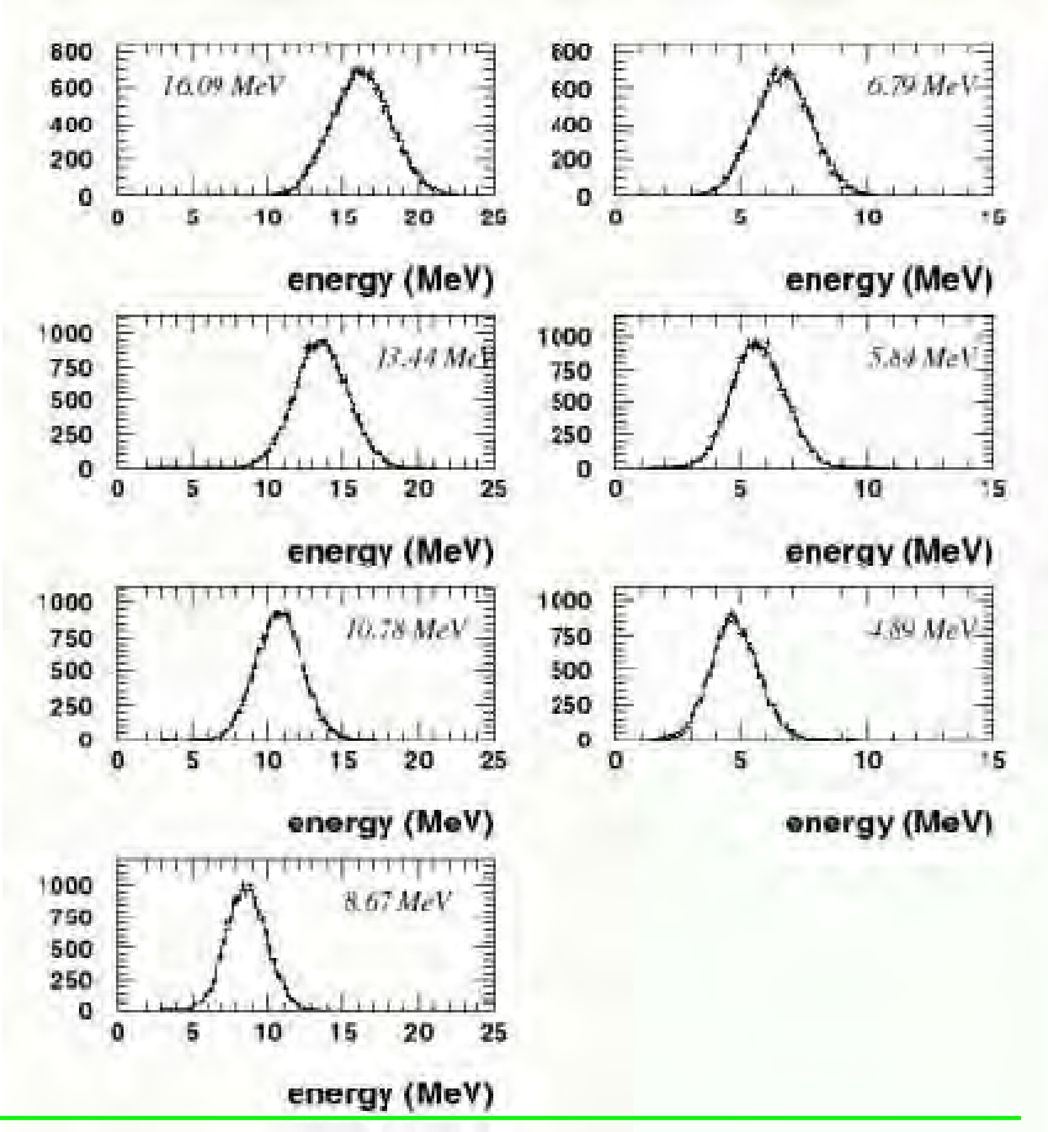
Wiązka wprowadzana pionowo w kilku wybranych punktach.



Super-Kamiokande

Kalibracja

Wyniki kalibracji przy pomocy akceleratora



Rozdzielczość energetyczna

- 18.4% przy 5 MeV
- 14.2% przy 10 MeV
- 11.3% przy 20 MeV

Tłumacząc to na parametry kalorymetru

$$\frac{\sigma}{E} \approx \frac{1.2\%}{\sqrt{E[GeV]}} \oplus 7.6\%$$

Super-Kamiokande

Kalibracja

Wada akceleratora: tylko wybrane pozycje i jeden kierunek wiązki (pionowy).

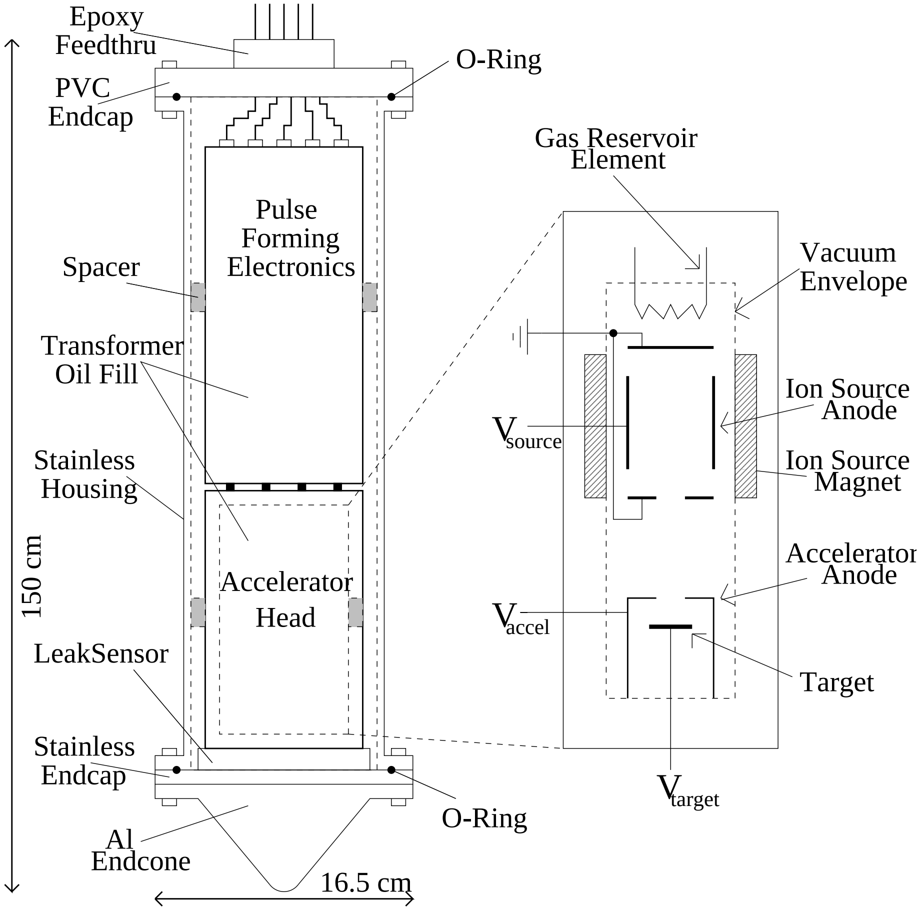
Drugie narzędzie: “generator DT” - źródło neutronów.

$$^{3}H + {}^{2}H \rightarrow {}^{4}He + n$$

Izotropowy strumień neutronów 14.2 MeV.

W oddziaływaniu z tlenem (w wodzie):

$$n + {}^{16}O \rightarrow p + {}^{16}N$$

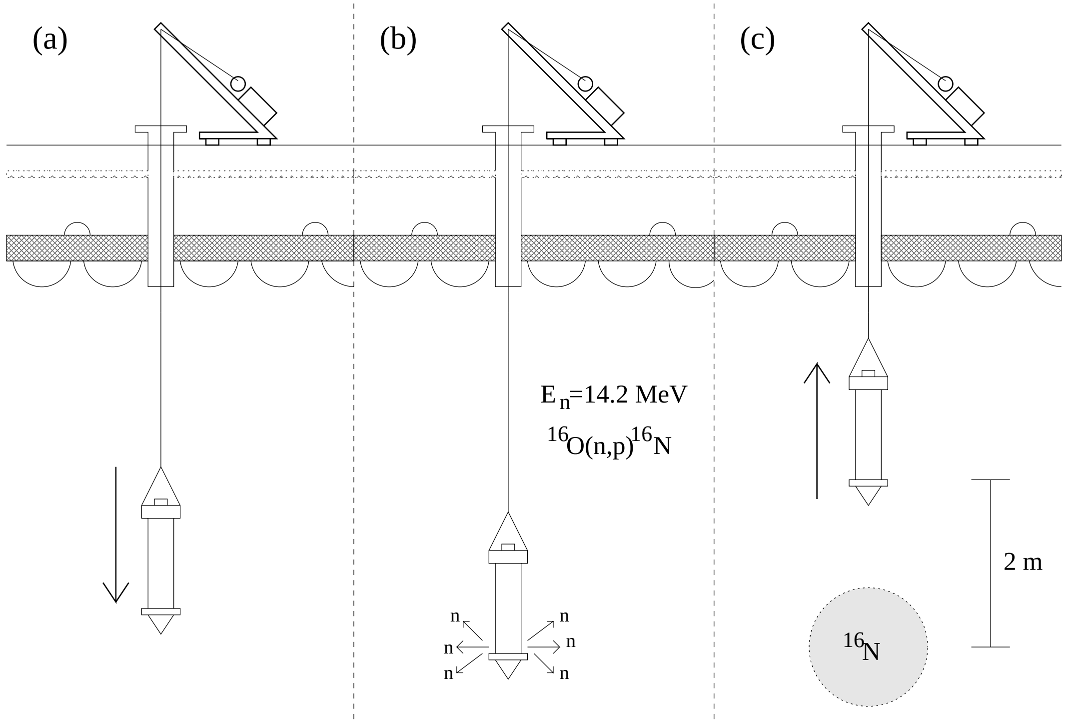


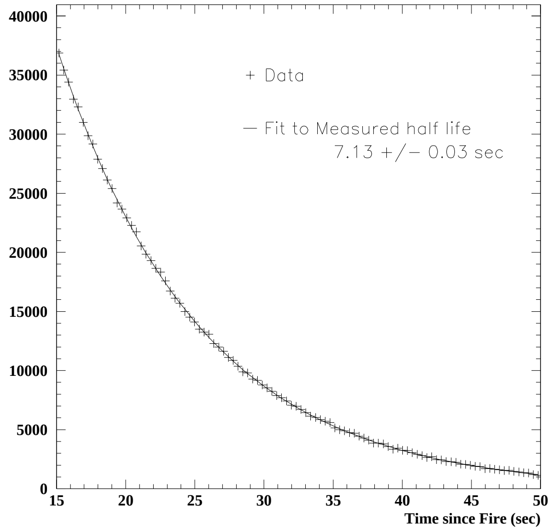
Super-Kamiokande

Kalibracja

Rozpady ${}^{16}N$ dokładnie znane:

- 66%: 6.129MeV γ + 4.29MeV β
- 28%: 10.419MeV β





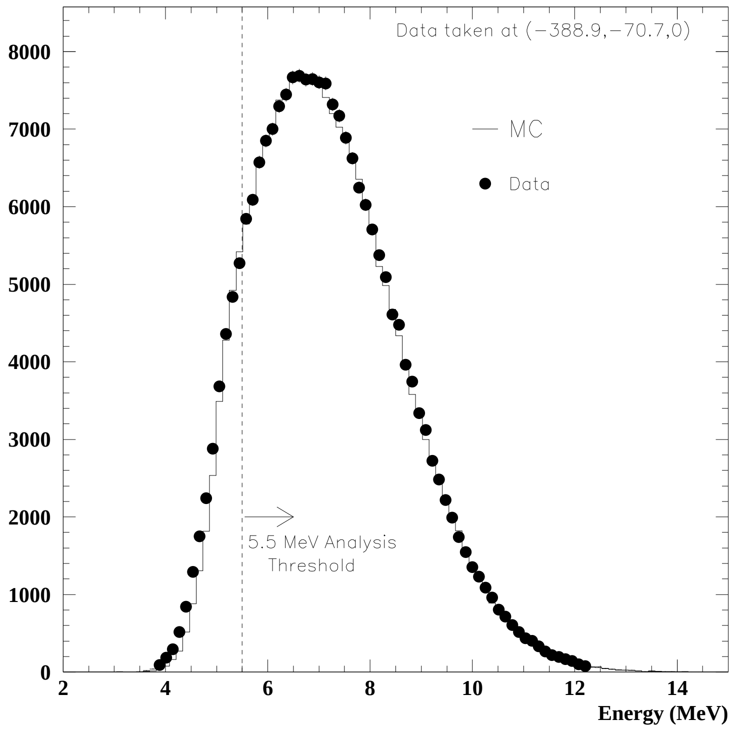
Rozpady ${}^{16}N$ mierzone po wyciągnięciu “generatora”

Super-Kamiokande

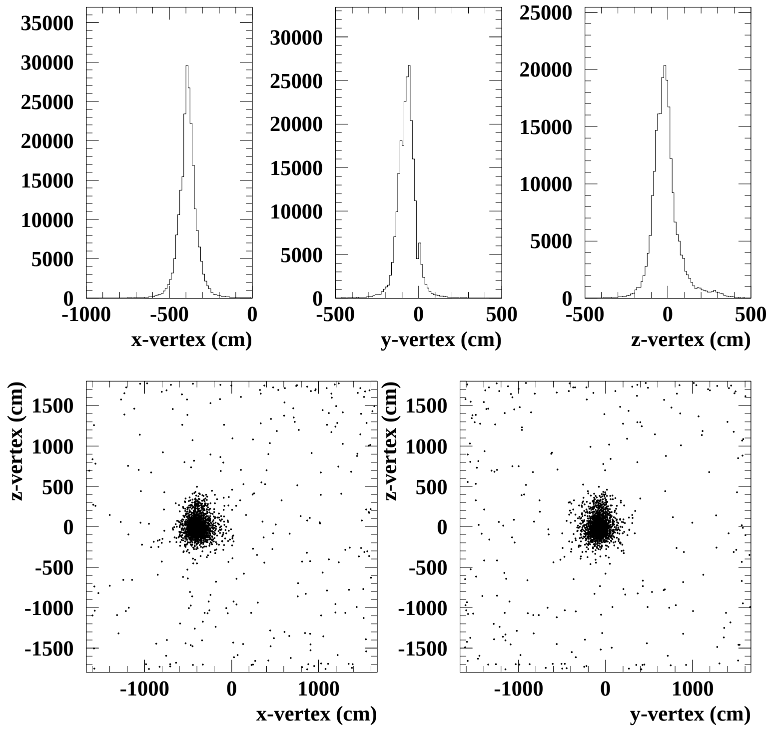
Kalibracja

Mierzone rozkłady dla przypadków kalibracyjnych ^{16}N:

Energii



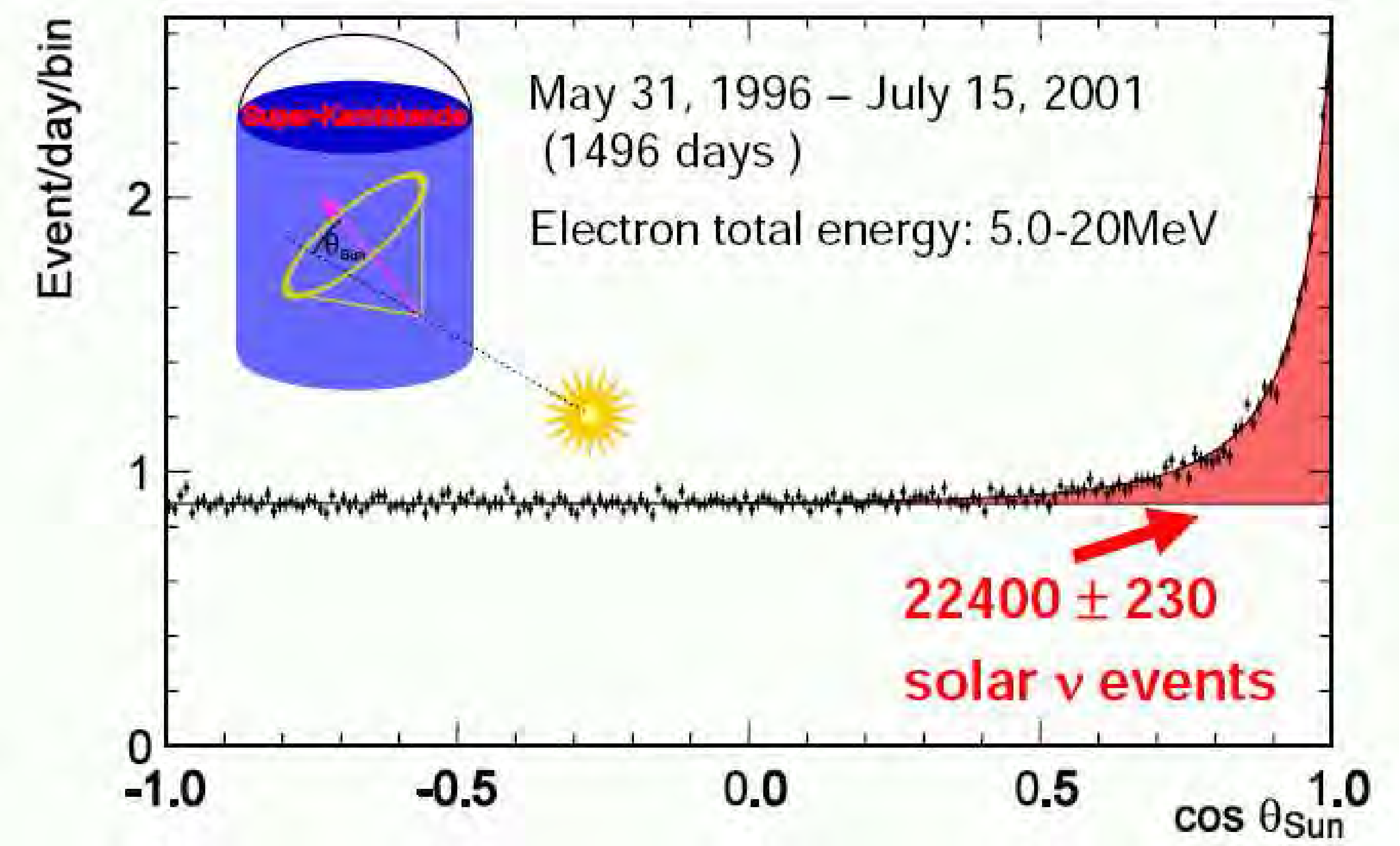
Położenia wierzchołka



Super-Kamiokande

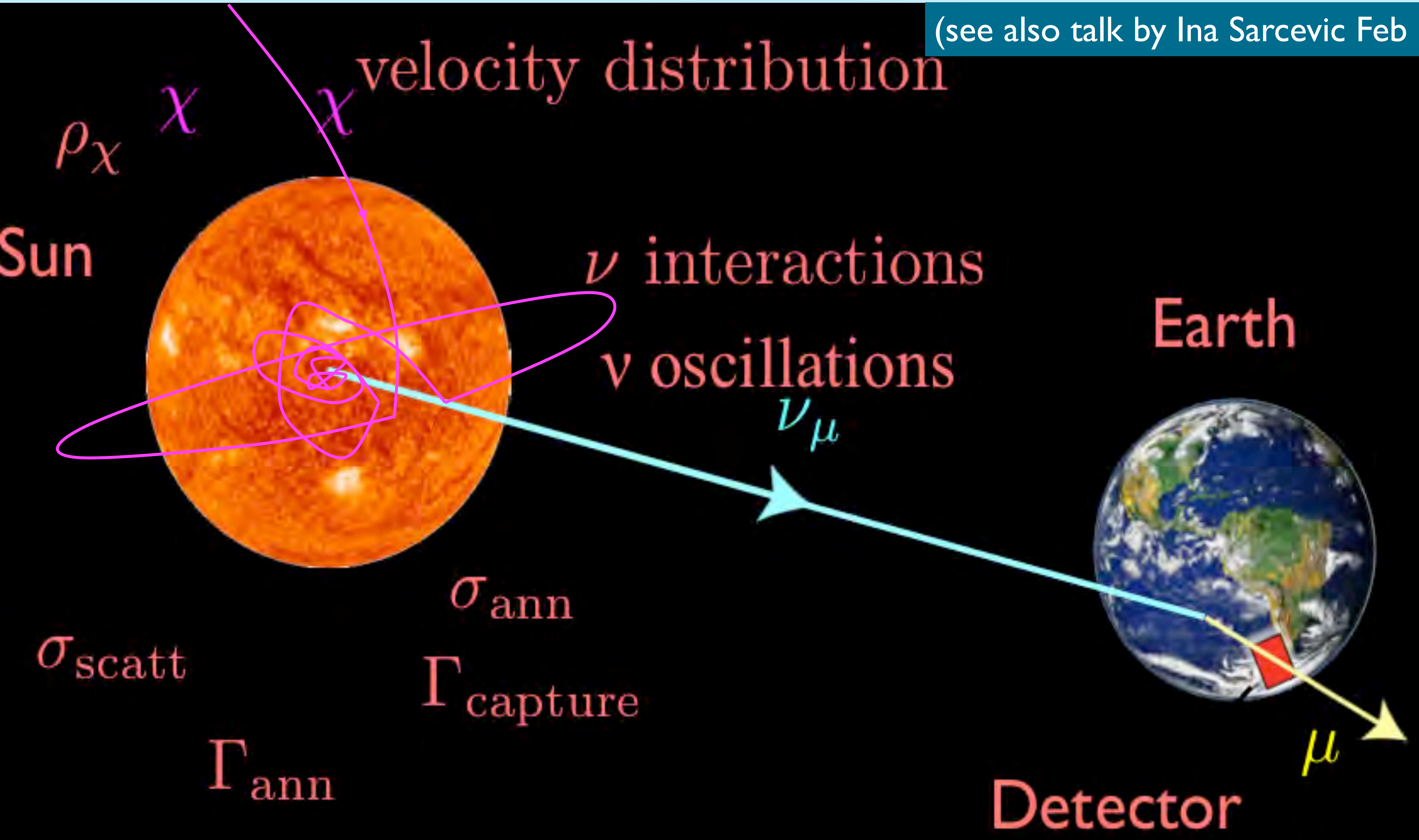
Obserwacja neutrin słonecznych

Oddziaływania neutrin słonecznych możemy odróżnić od oddziaływań neutrin atmosferycznych mierząc kąt rozproszenia elektronu względem kierunku od słońca:



Solar WIMP Signal

(see also talk by Ina Sarcevic Feb 6, 2013)



Freese '86
Krauss, Srednicki & Wilczek '86
Gaisser, Steigman & Tilav '86

Silk, Olive and Srednicki '85
Gaisser, Steigman & Tilav '86

Dark Matter annihilation to neutrinos

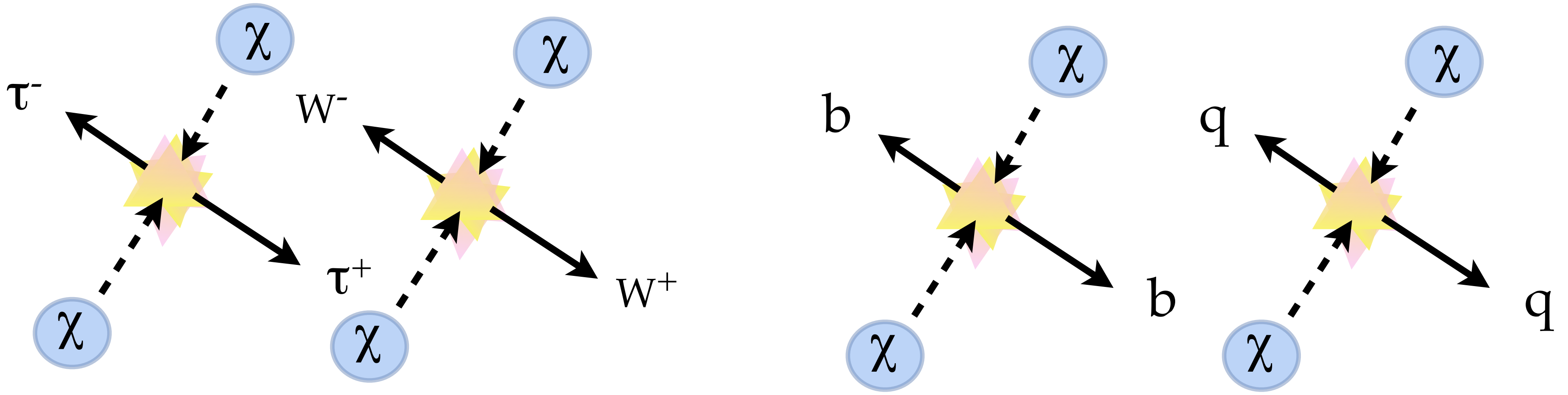
… where they may come from?

Search for neutrinos
from DM annihilation (approaches)

Directional flux
related to regions of increased DM density:
- core of Sun, Earth, Galaxy Center
- constrain SD/SI $\sigma_{\chi n}$

Diffuse flux:
- flux averaged over large cosmic volumes (many galactic halos) or over Milky Way
- constrain DM self-annihilation cross section $<\sigma \cdot v>$

Dark Matter Annihilation in the Sun



high energy neutrinos from annihilation / decay products

$\nu\nu$ $\tau^-\tau^+$ W^-W^+ bb qq e^+e^-

highest energy neutrinos

fewest neutrinos

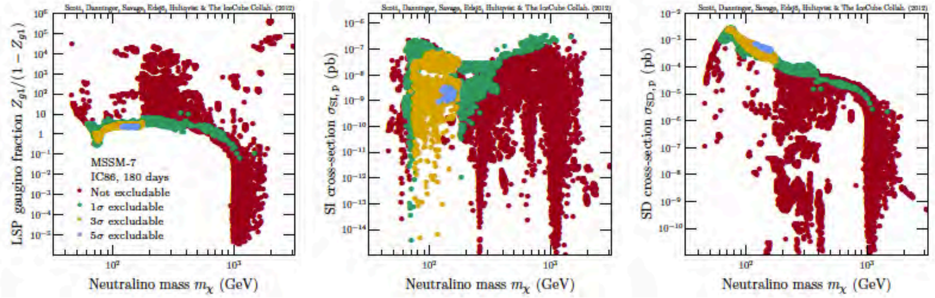
Benchmarks
Br 100%

Hard channel

Soft channel

Specific
Model

$$\mathcal{L}_{\rm total}(n_{\rm tot}, \Xi|\psi) = \mathcal{L}_{\rm num}(n_{\rm tot}|\psi) \prod^{n_{\rm tot}} \mathcal{L}_{{\rm ang},i}(\phi'_i|\psi)\, \mathcal{L}_{{\rm spec},i}(N_i|\psi)$$



see: Scott, Savage, Edsjo and IceCube Collaboration "Use of event-level neutrino telescope data in global fits for theories of new physics" arXiv1207.0810

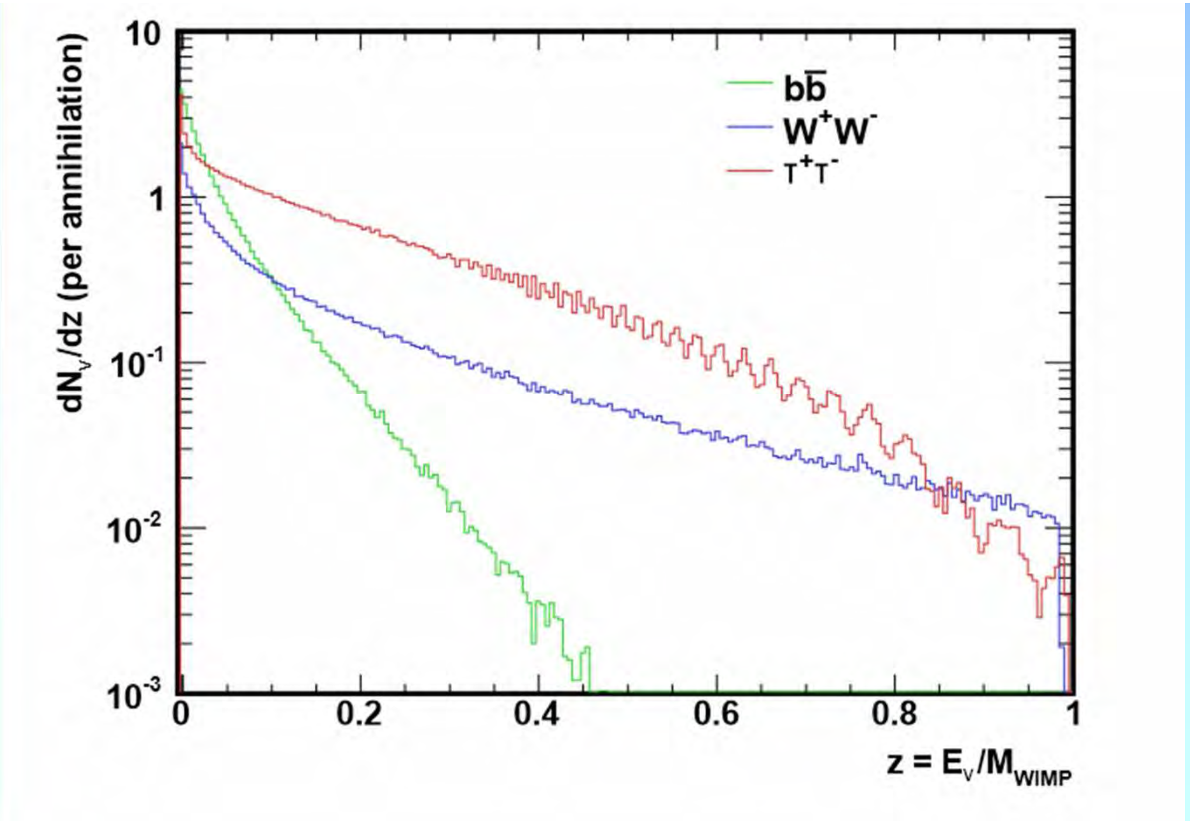
Relatively
model
independent

low energy neutrinos from hadronic shower

see: Rott, Siegal-Gaskins, Beacom arXiv1208.0827

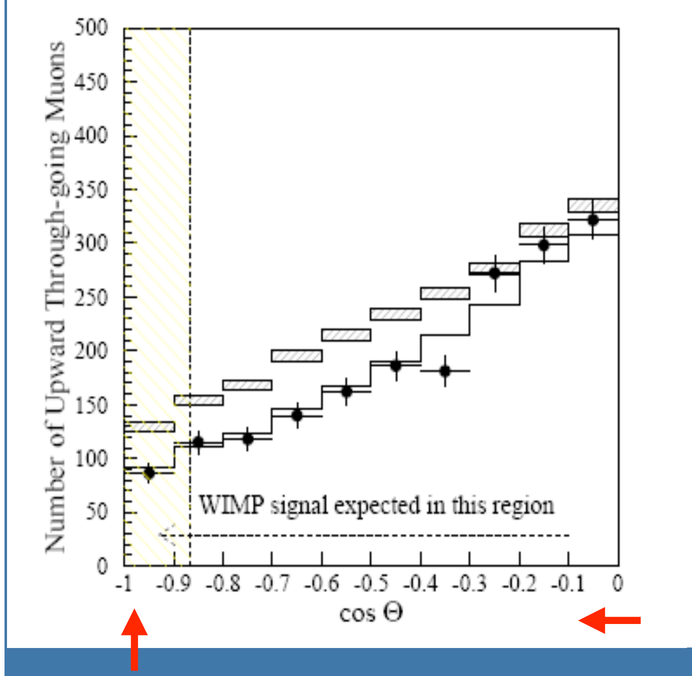
Neutrino signal from WIMP annihilations

- WIMPSIM package (Blennow, Edsjö, Ohlsson, 03/2008) used to generate events in the Sun in a **model-independent way**
- Annihilations into b quarks (soft spectrum) and τ leptons, WW/ZZ bosons (hard spectrum) **used as benchmarks**
- Take into account ν **interactions** in the Sun medium, **regeneration of ν_τ** in the Sun and ν **oscillations**

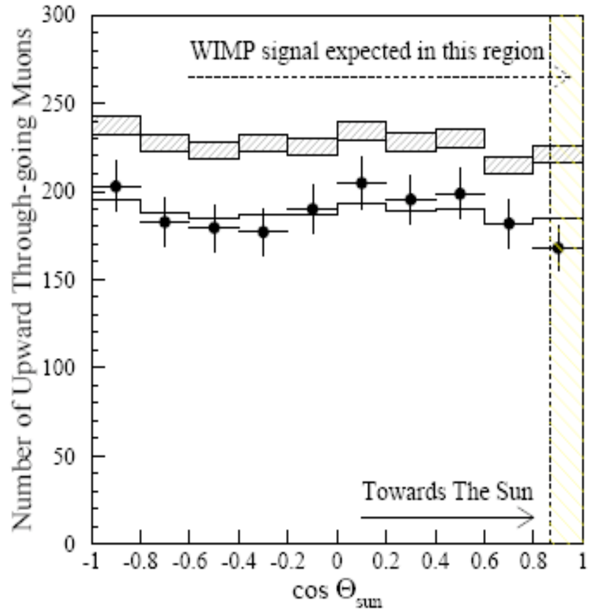


Search for WIMPs in SuperK (directional flux)

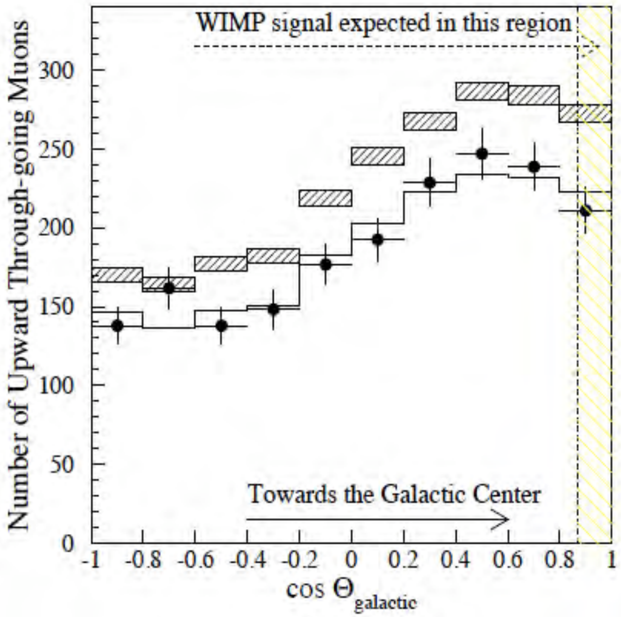
EARTH



SUN



GC



(*) S.Desai et al., Phys.Rev. D70 (2004) 083523

- Search for excess of neutrinos in SK1 data (1679.6 live days)
- WIMP mass range 18GeV-10TeV -> neutrino energy: ~5 GeV – 5 TeV
- Data sample: upward through-going muons
- Currently new analysis: more data, lower energy neutrinos also included (T.Tanaka)

Diffuse search idea

- Investigation is limited to „most optimistic" but model independent WIMP annihilation channel

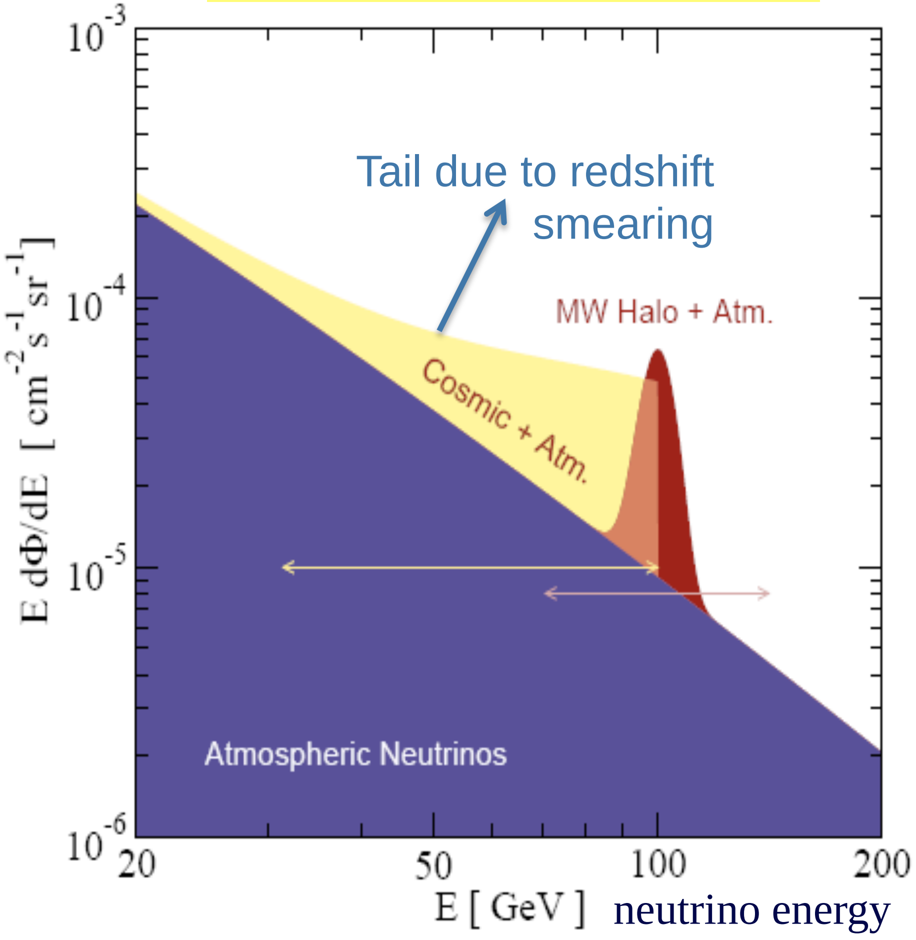
$$\chi + \chi \rightarrow \nu + \bar{\nu}$$

neutrino energy = WIMP mass

signal is isotropic

- Relevant for DM diffuse annihilation and also for DM decay modes
- Due to distinctive energy spectra of WIMP-induced neutrinos coming from that „golden channel" it is possible to test data against characteristic distortions in energy and cos spectra
- Use method of min χ^2 to find best allowed WIMP contribution
- Derive conservative upper limit on WIMP total self-annihilation cross section $<\sigma V>$, lifetime τ_{DM}

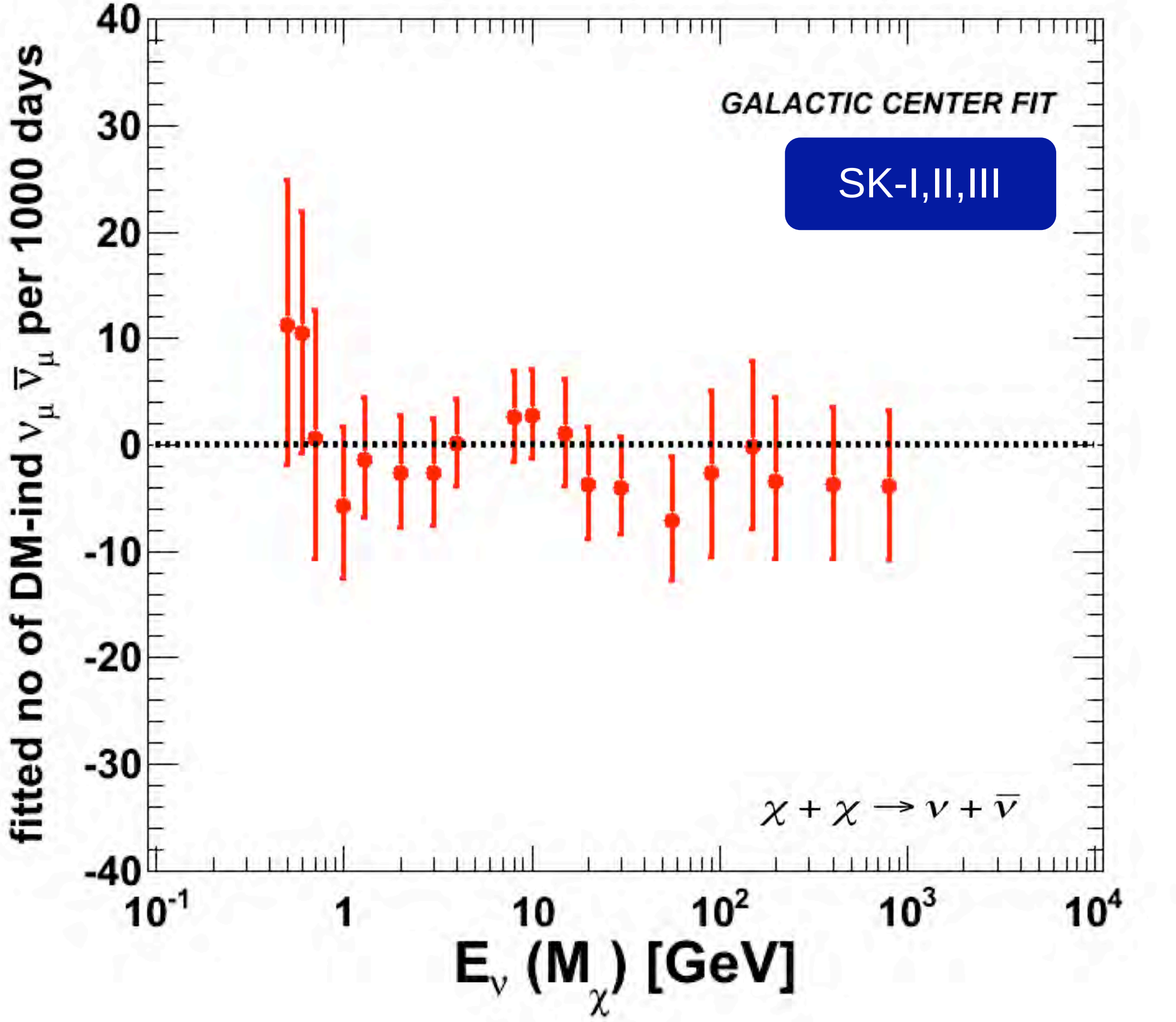
Illustration of 100 GeV DM annihilation signal



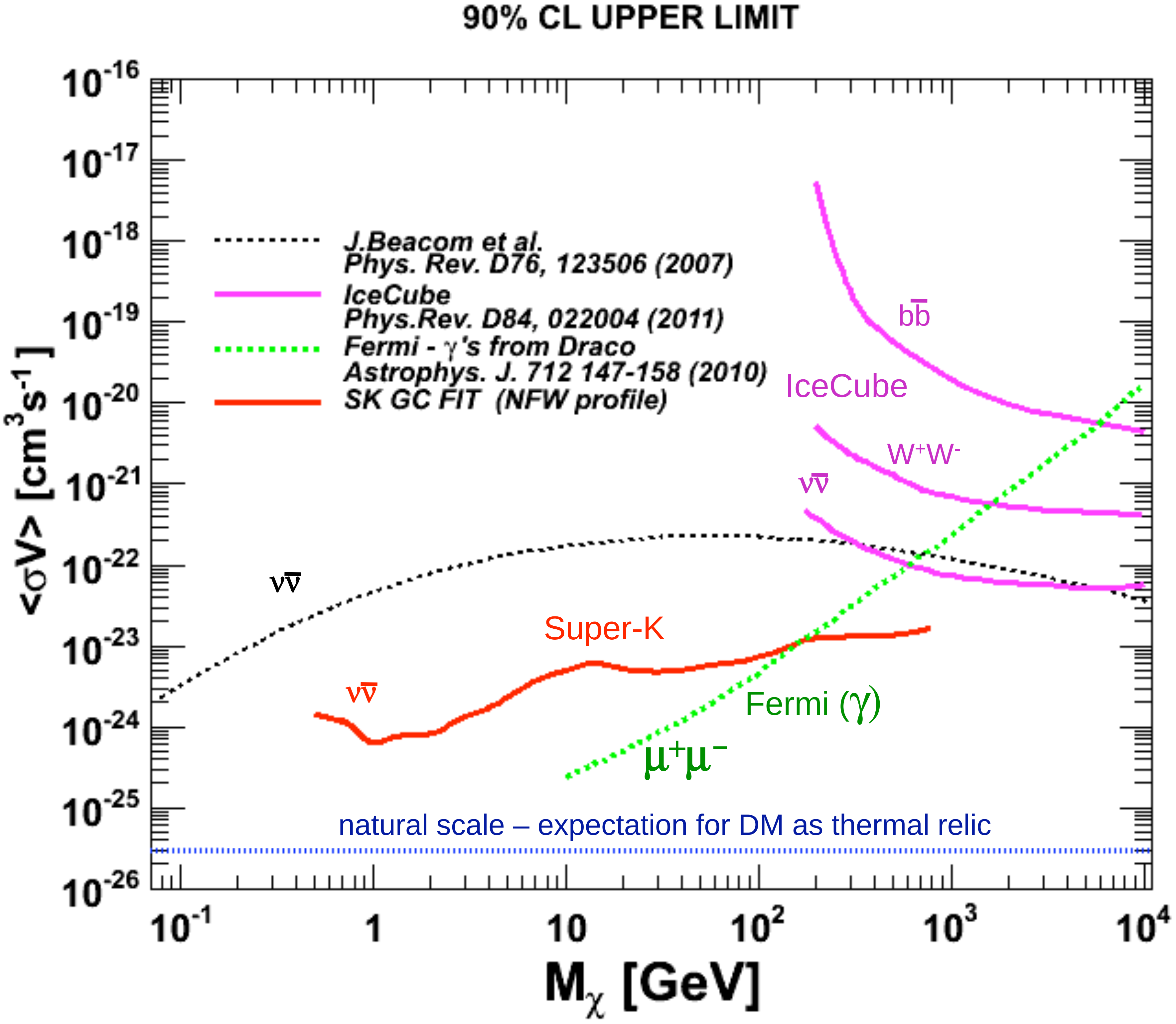
(*) ***J.F.Beacom et al., Phys. Rev. D76, 123506 (2007)***

Fitted # of DM-induced neutrinos

- FIT based on Momentum & $\cos\theta_{GC}$ distributions of all SK samples, systematics included
- Fitted:
  - WIMP signal normalization
  - ATM MC normalization and shape via 119 systematic uncertainty terms but Δm^2_{23}, $\sin^2 2\theta_{23}$ not varied
- No allowed excess of DM-ind ν's for M_χ in range 0.5 GeV – 800 GeV
- FIT consistent with 0 → upper limit on DM-ind neutrino flux from Milky Way halo (ϕ) → upper limit on WIMP self-annihilation cross section $<\sigma_A V>$



SK data livetime: FC/PC 2806 days, UPMU 3109 days


90% CL UPPER LIMIT
<σV> [cm^3 s^-1]
10^-16
10^-17
10^-18
10^-19
10^-20
10^-21
10^-22
10^-23
10^-24
10^-25
10^-26
M_χ [GeV]
10^-1
1
10
10^2
10^3
10^4
J.Beacom et al.
Phys. Rev. D76, 123506 (2007)
IceCube
Phys.Rev. D84, 022004 (2011)
Fermi - γ's from Draco
Astrophys. J. 712 147-158 (2010)
SK GC FIT (NFW profile)
bb̄
IceCube
W+W-
νν̄
νν̄
Super-K
νν̄
Fermi (γ)
μ+μ−
natural scale – expectation for DM as thermal relic

- Beginning in the 1970s, the dream of **high-energy neutrino astronomy** fascinated a small group of visionaries.
- 1990: AMANDA (**Antarctic Muon and Neutrino Detector Array)** collaboration formed.
- Very clear since the beginning the need of **km^3 scale neutrino telescope**
- **2000:** AMANDA completed at the South Pole, first demonstration of feasibility of a large neutrino telescope in the ice
- **May 30th, 2008:** Antares detector completed!
- 2002: IceCube project approved. The first km^3 scale neutrino telescope.
- 2004-2010 drilling of IceCube strings
- 18th of December 2010, IceCube neutrino telescope completed!

AMANDA

(Antarctic Muon And Neutrino Detector Array)

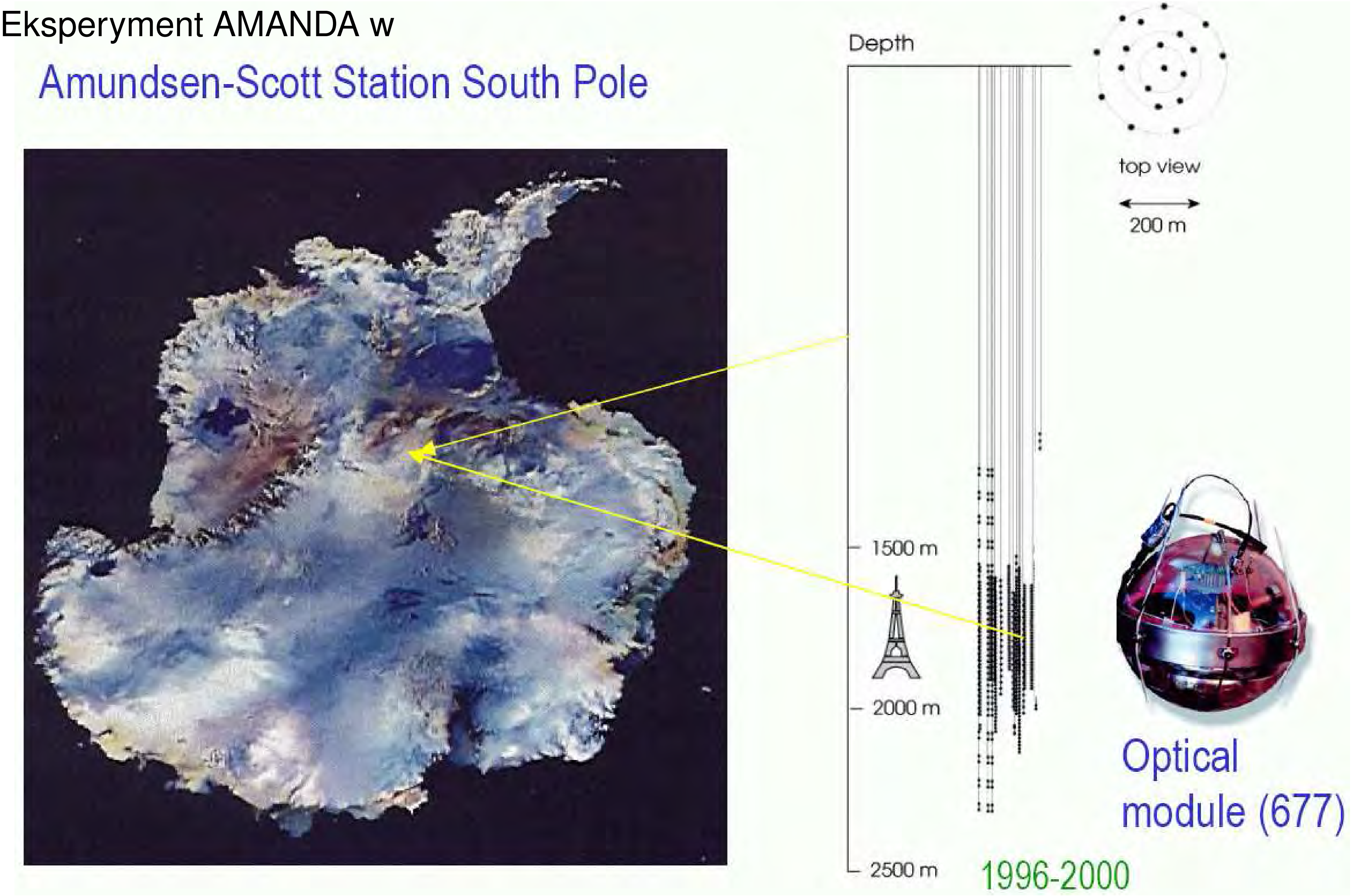
677 modułów na 19 “strunach”,
1500–2000 m pod lodem (biegun południowy)

promieniowanie Czerenkowa mierzone przez skierowane do dołu fotopowielacze

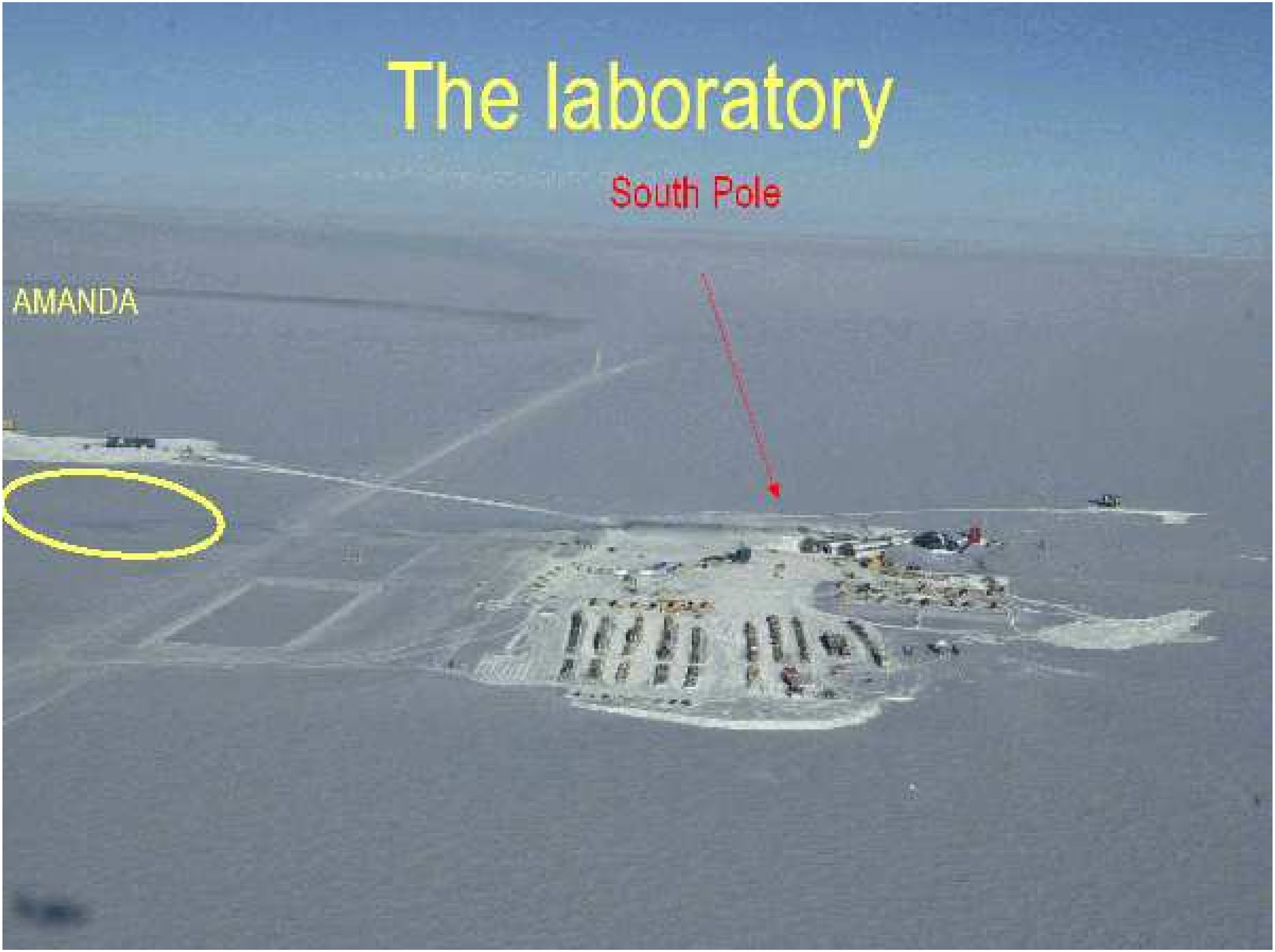
Obszar aktywny: ok. 40 mln. ton lodu (!)

Rejestracja mionów o energiach $\geq$50 GeV.

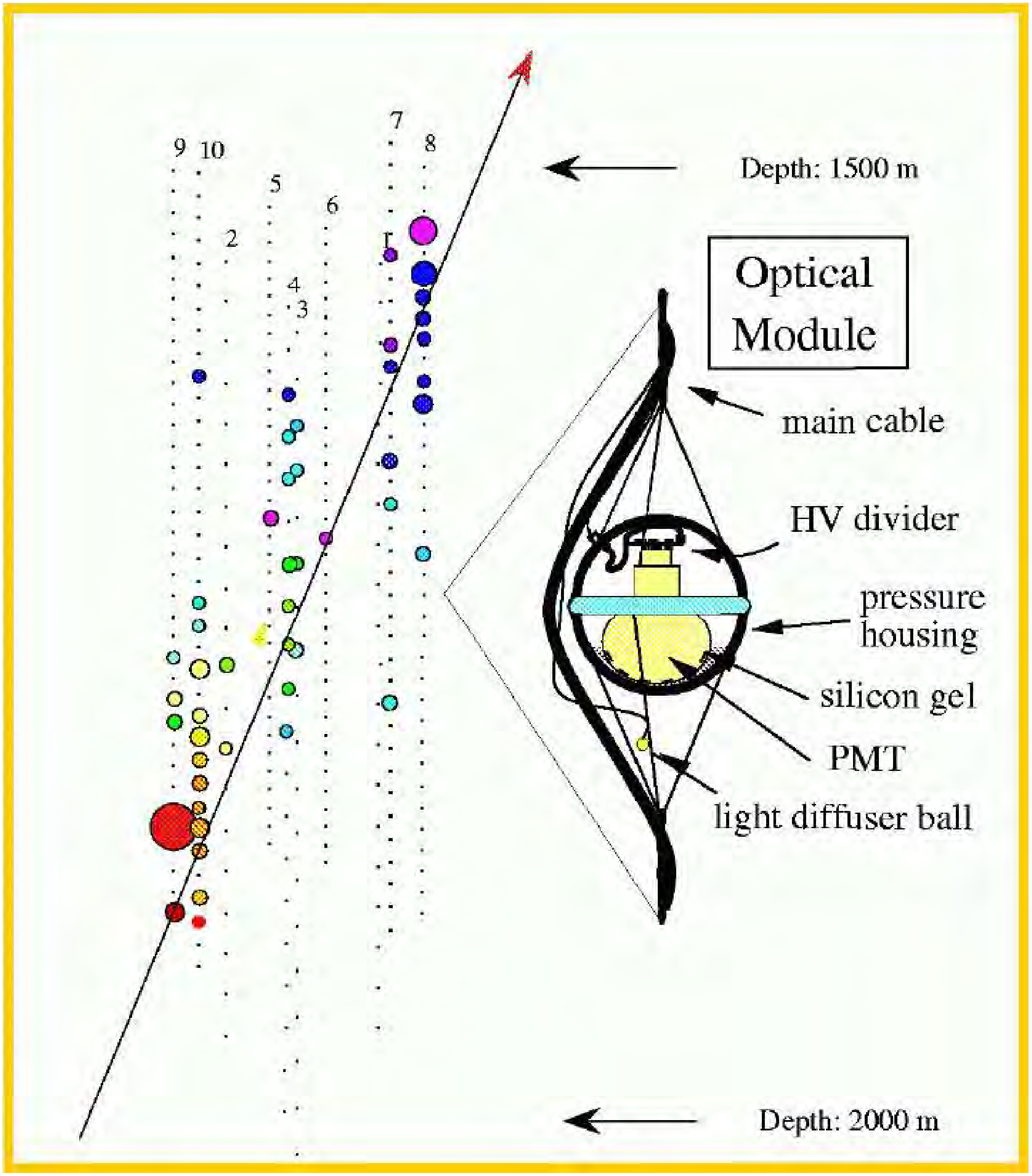
Eksperyment AMANDA w



The laboratory



Przypadek mionu z oddziaływania wysokoenergetycznego neutrina



```
No external geometry file is opened.
Detector: amanda-b-10, 19 strings, 680 modules
Data file: he_deff.f2k
Displaying data event 1425281 from run 336
Recorded yr/dy: 2000/170
  59857.5405130 seconds past midnight.
Before cuts:  264 hits,  264 OMs
After cuts :  264 hits,  264 OMs
```

200 TeV ν_e candidate

AMANDA

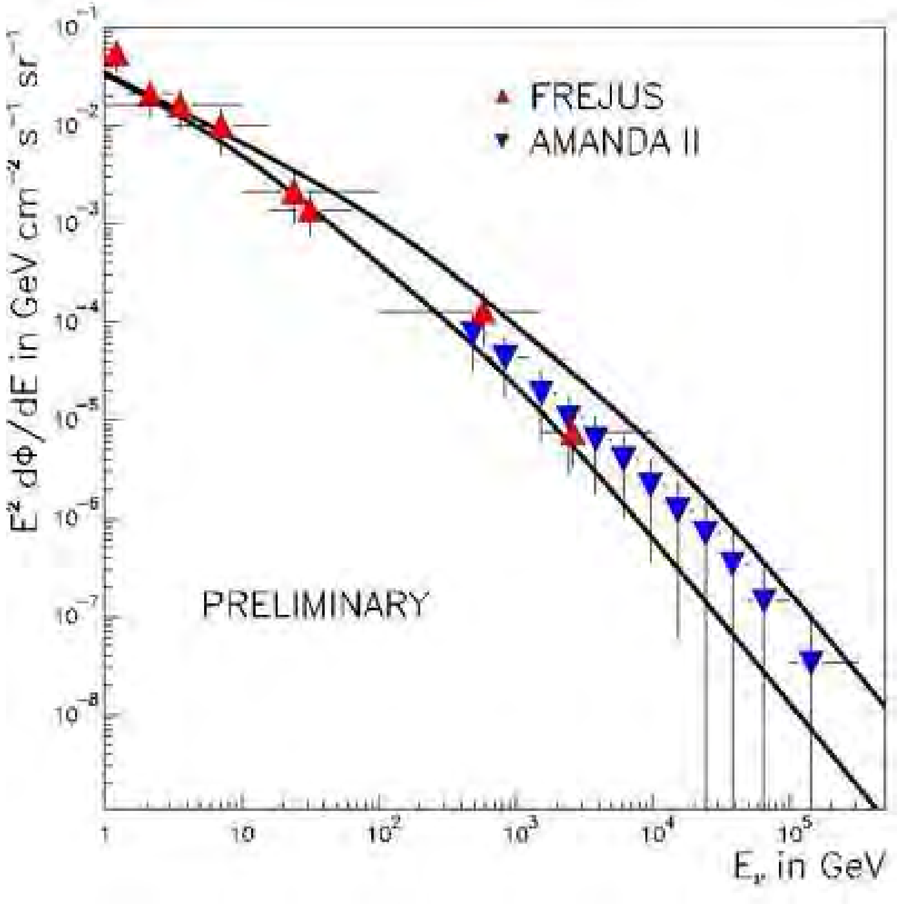
Badania

Duże odległości między licznikami powodują, że detektor czuły jest tylko na neutrina o bardzo wysokiej energii - wyprodukowane w ich oddziaływaniach cząstki muszą mieć zasięg porównywalny z rozmiarami detektora.

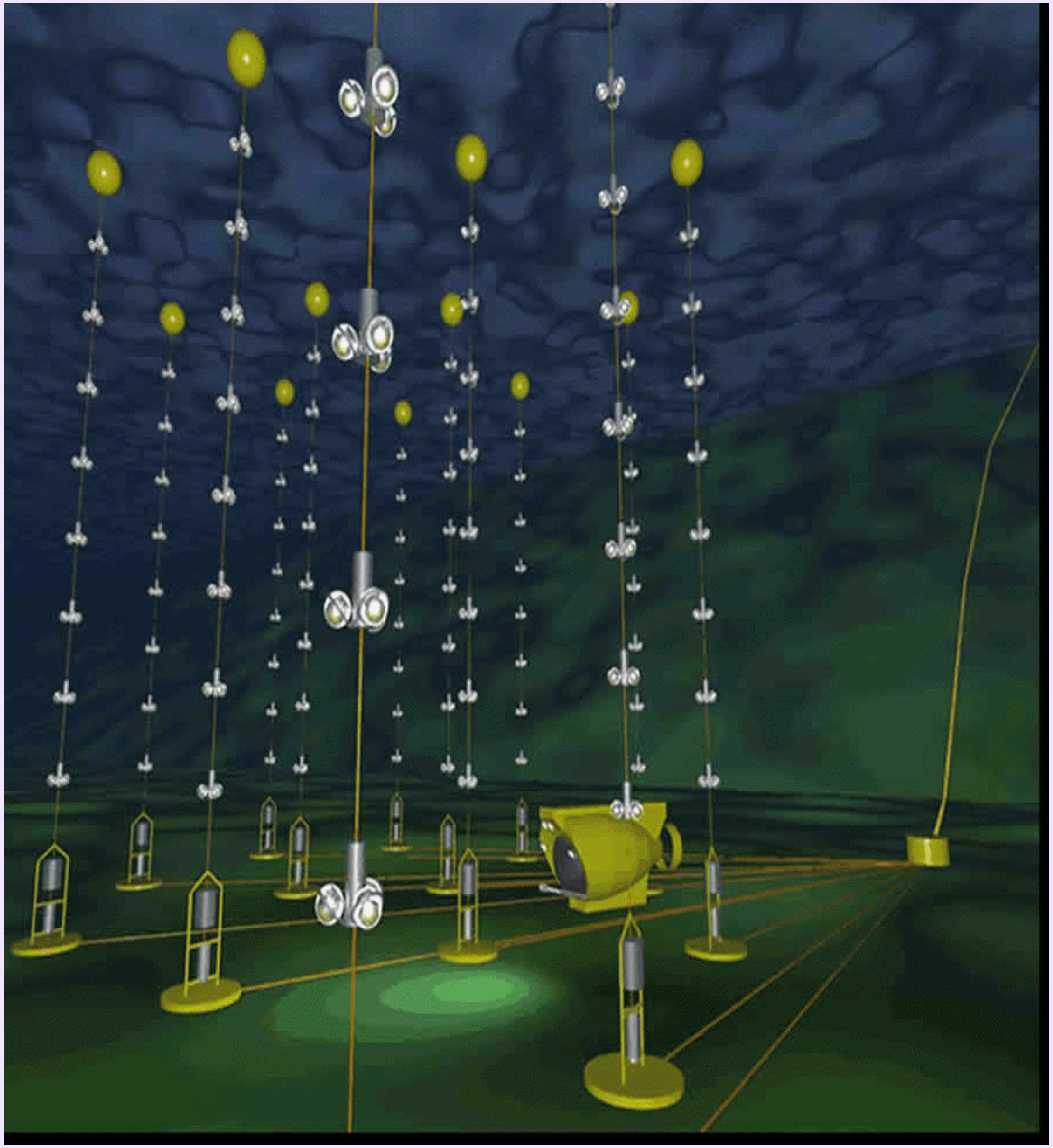
Poszukiwanie neutrin stowarzyszonych z:

- wybuchami supernowych
- błyskami gamma (GRB)
- gwiazdami neutronowymi
- ...

Mierzony rozkład energii neutrin



ANTARES Detector



In Mediterranean Sea

40 km from Toulon

2.5 km under water

12 Lines (885 PMTs)

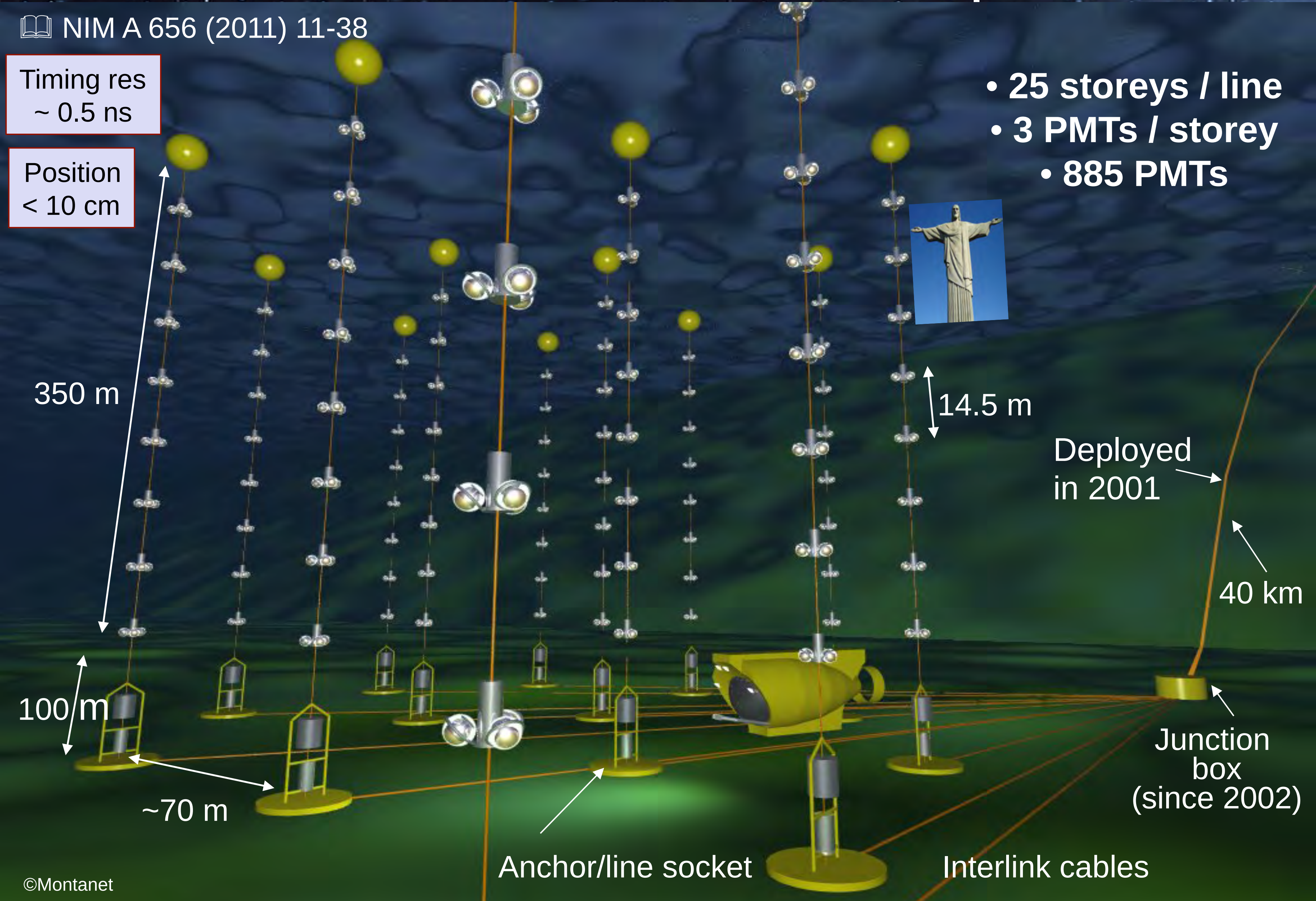
Line length ~450 m

Optimized for muons
at TeV energies

Taking high quality
data since 2007

The ANTARES Neutrino Telescope

📖 NIM A 656 (2011) 11-38



Timing res
~ 0.5 ns

Position
< 10 cm

- 25 storeys / line
- 3 PMTs / storey
- 885 PMTs

©Montanet

The ANTARES Site

Toulon

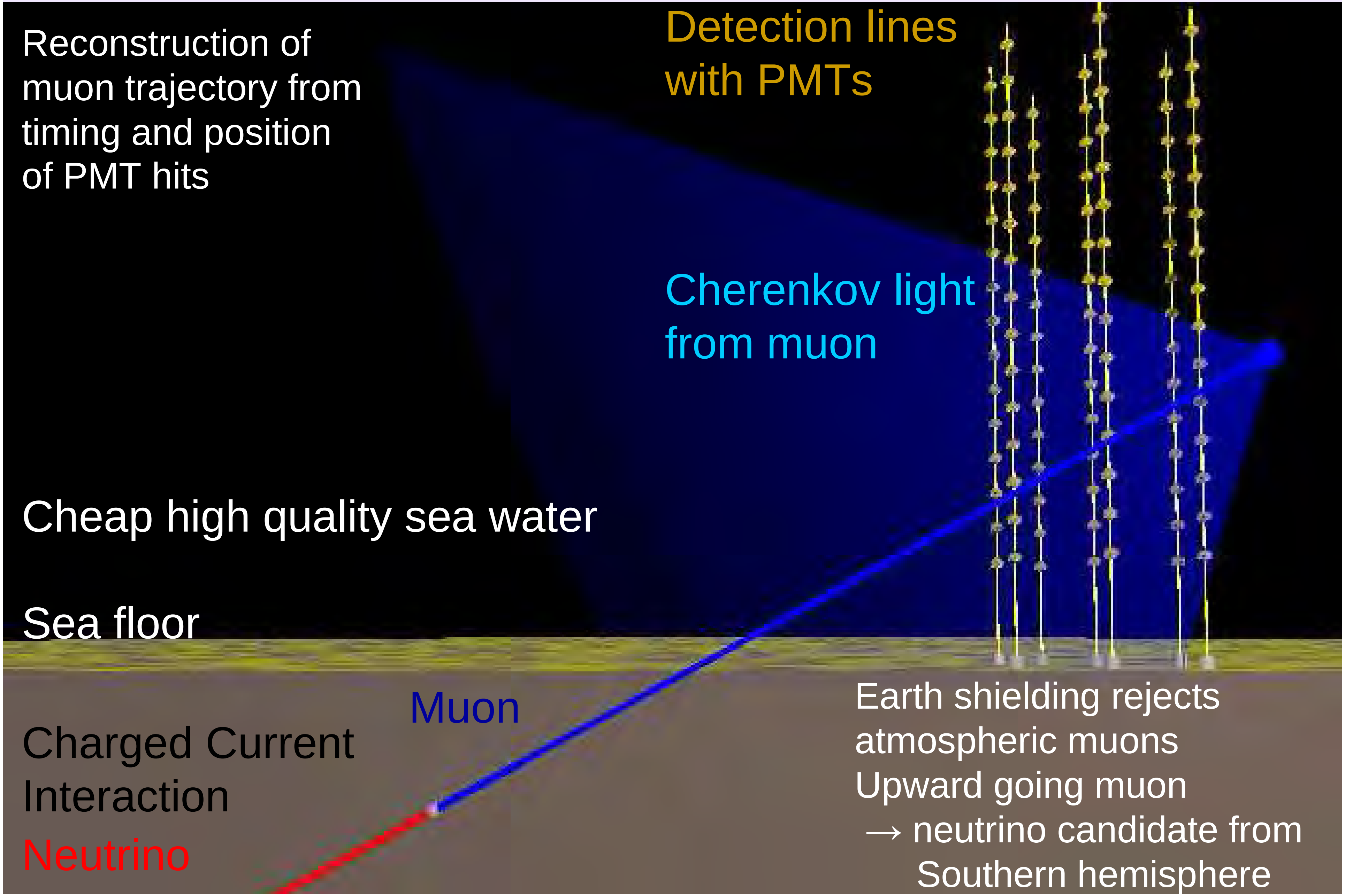
M. Pacha Institute

ANTARES

Electro-optical Cable of 40 km

42 50'N, 6 10'E

Neutrino Detection



Reconstruction of
muon trajectory from
timing and position
of PMT hits

Detection lines
with PMTs

Cherenkov light
from muon

Cheap high quality sea water

Sea floor

Muon

Charged Current
Interaction

Neutrino

Earth shielding rejects
atmospheric muons
Upward going muon
→ neutrino candidate from
Southern hemisphere

Sources for DM searches

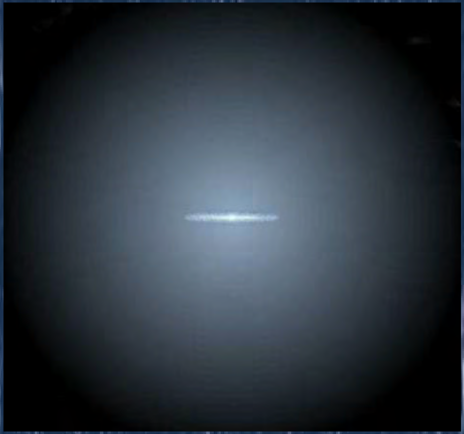
Sun

Earth

Galactic Centre

Dwarf galaxies

Galaxy clusters



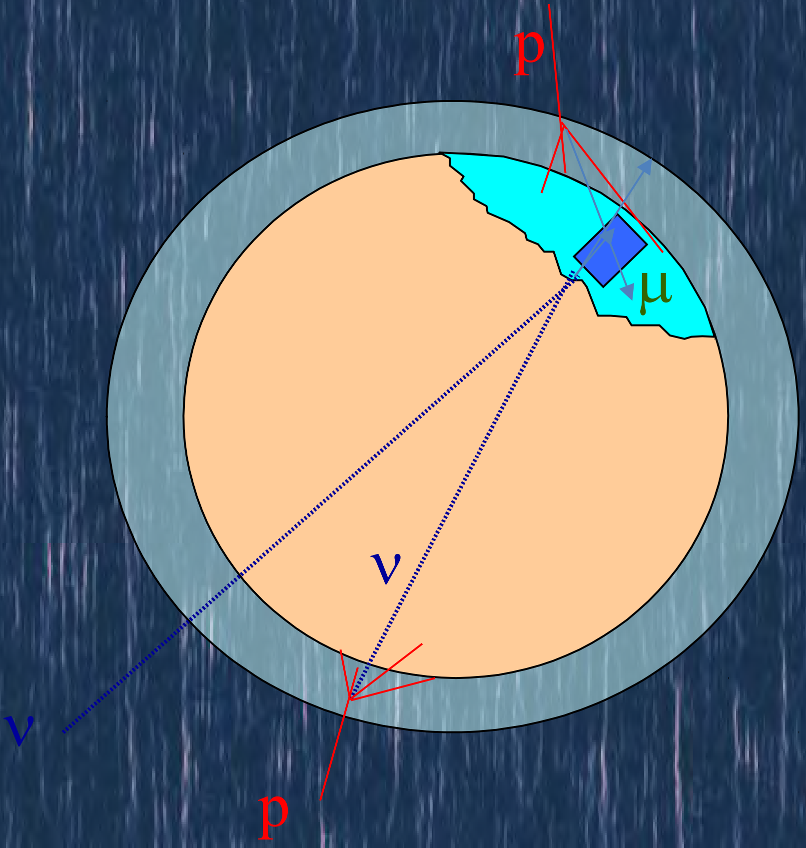
Galactic halo

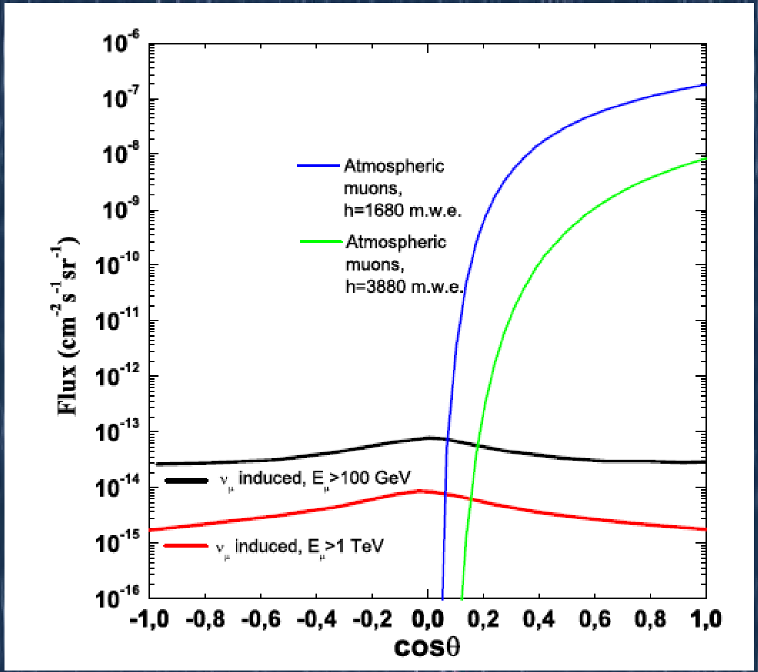
Physical background

- There are two kinds of background:
  - -Muons produced by cosmic rays in the atmosphere (→ detector deep in the sea and selection of up-going events).
  - -Atmospheric neutrinos (cut in the energy).

$$p \rightarrow \pi^{+}(+K^{+}...) \rightarrow \mu^{+} + \nu_{\mu}$$
$$\mapsto e^{+} + \overline{\nu}_{\mu} + \nu_{e}$$

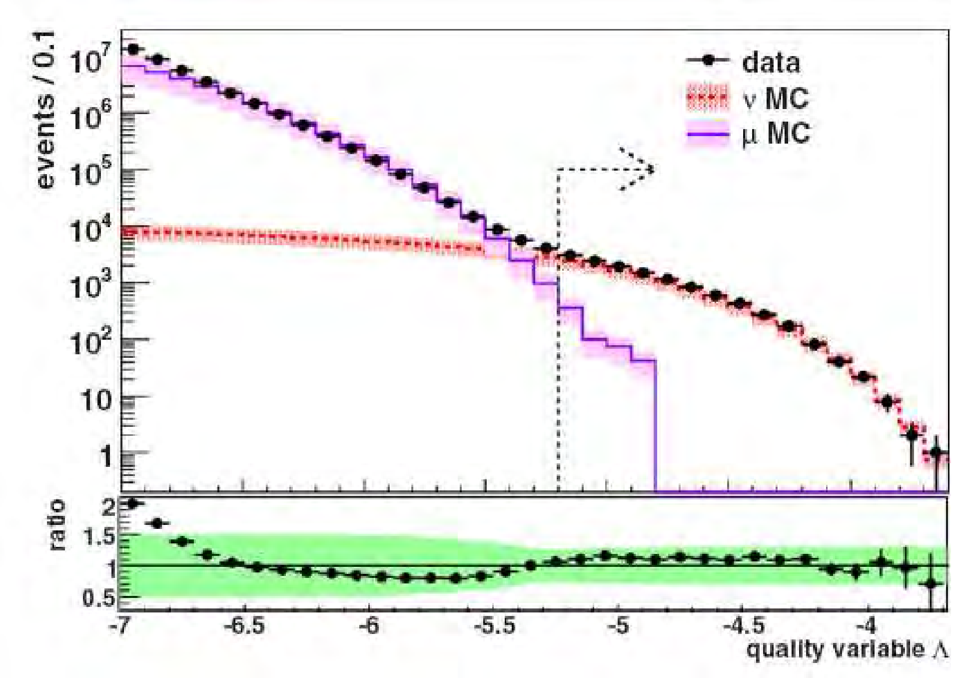
$$n \rightarrow \pi^{-}(+K^{-}...) \rightarrow \mu^{-} + \overline{\nu}_{\mu}$$
$$\mapsto e^{-} + \nu_{\mu} + \overline{\nu}_{e}$$



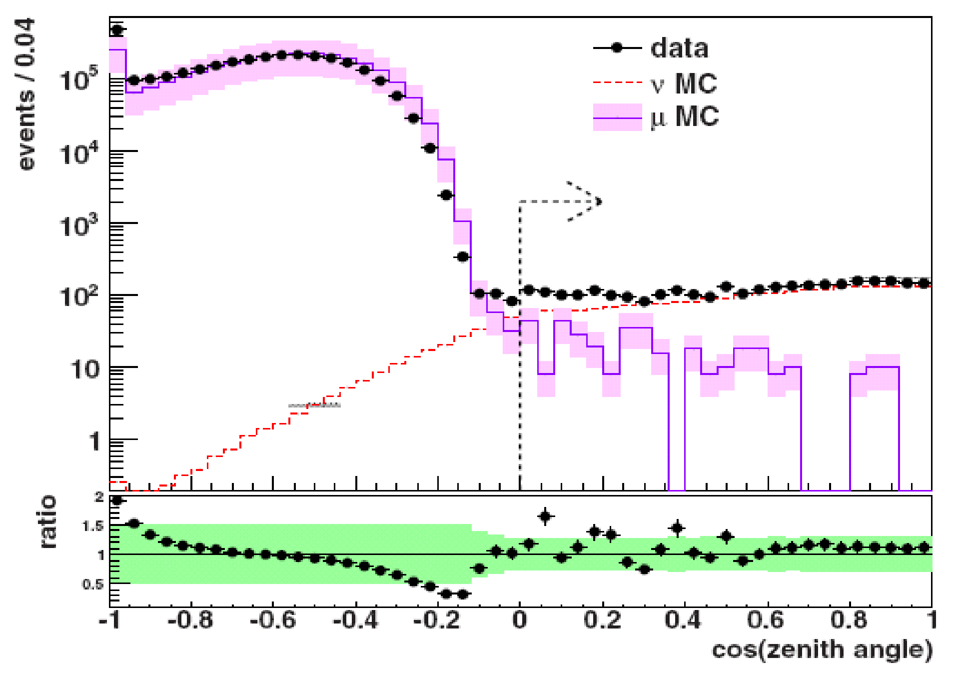


Upward Going Muons from Charged Current Neutrino Interactions

Tracks reconstructed by maximization of track likelihood
Likelihood = probability density of observed hit time residuals
Time residuals = difference between observed and expected time



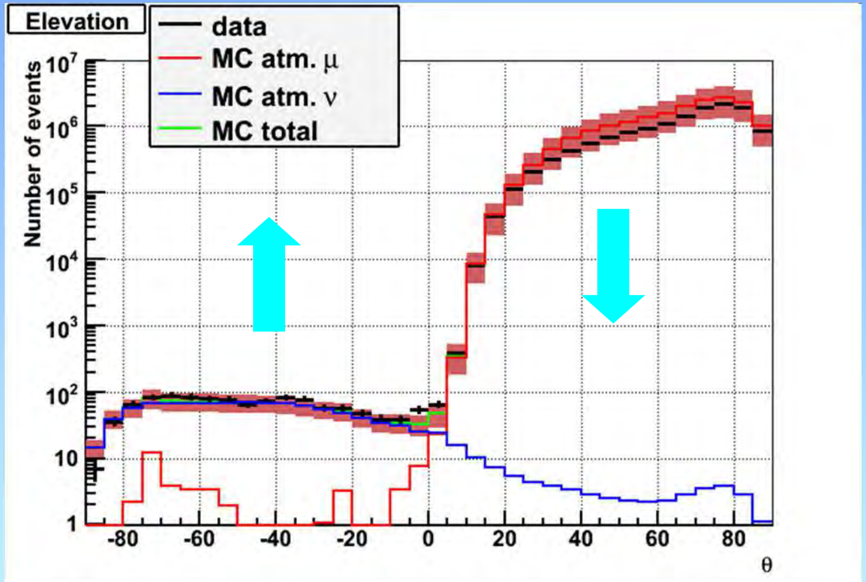
Cumulative distribution of reconstruction quality variable for upgoing tracks (2007-2010)



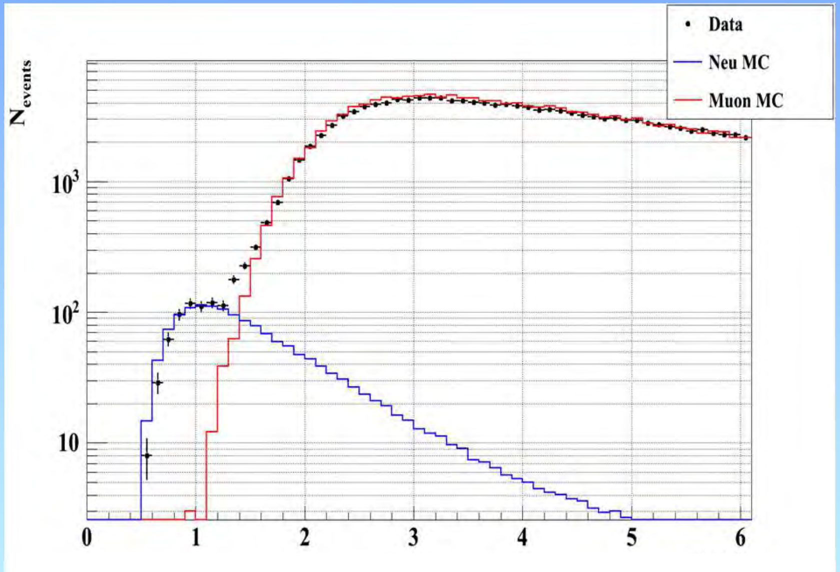
Distribution of zenith angle with quality variable > -5.2
→ ~3000 neutrino candidates

Event selection : background rejection

- Selection of neutrinos and rejection of atmospheric muons by selecting up-going tracks and cutting on track fit quality



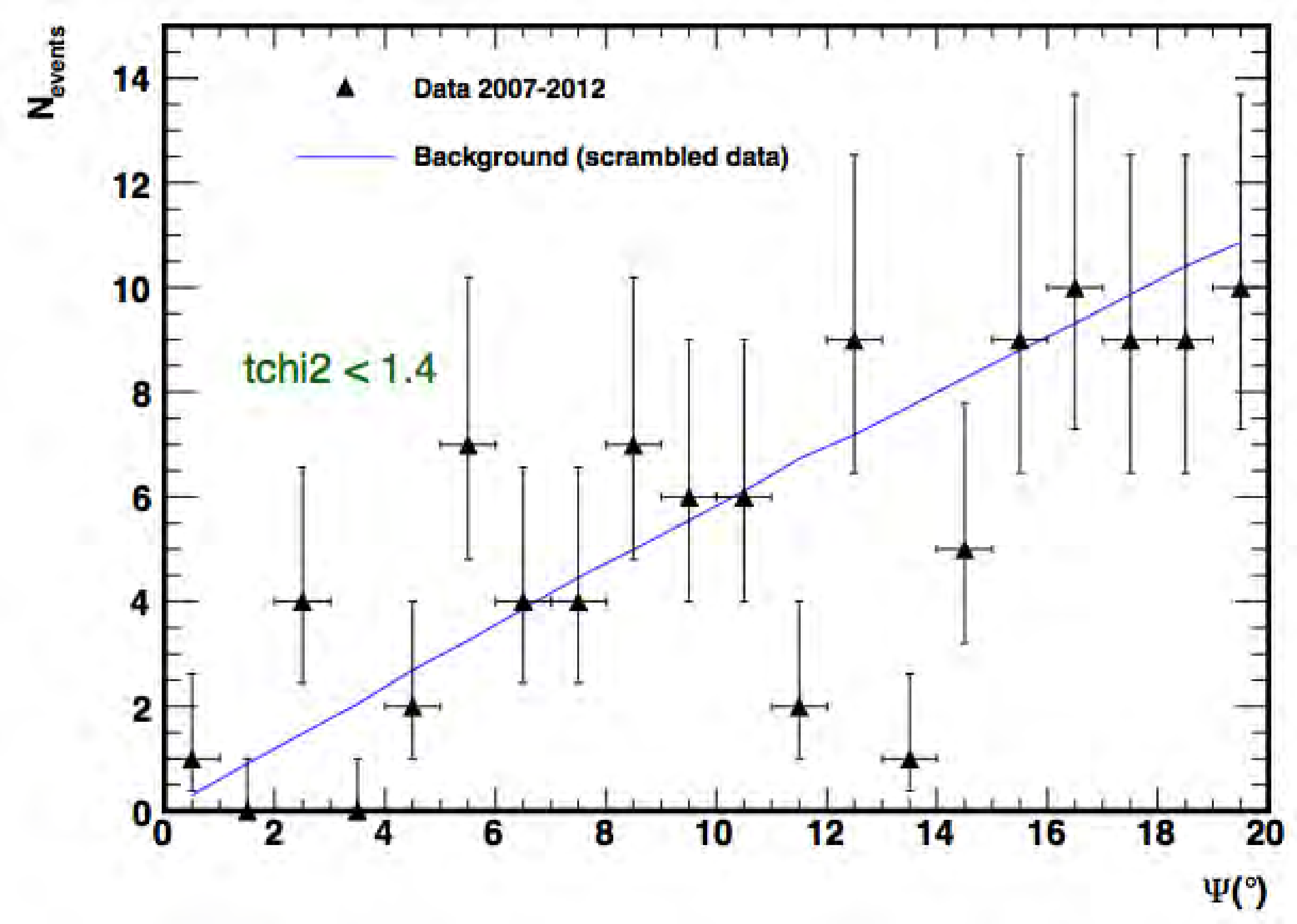
Elevation angle



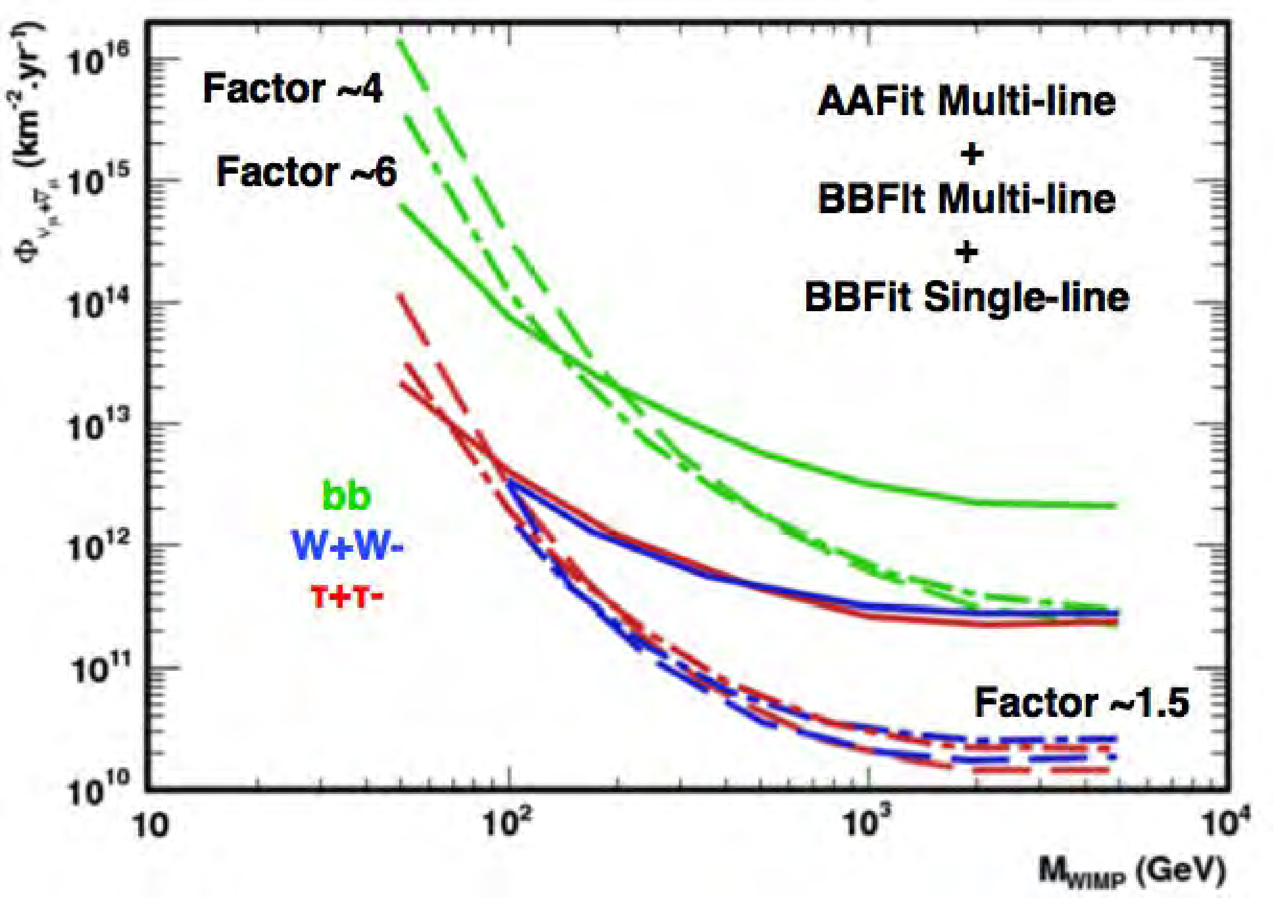
Track fit quality parameter

- Rejection of atmospheric neutrinos by looking into a cone towards the Sun direction (below horizon only)

Sun: unblinded data



Sun: limits on flux



Cross section calculation

Differential neutrino flux is related with the annihilation rate as:

$$\frac{d\phi_\nu}{dE_\nu} = \frac{\Gamma}{4\pi d^2}\frac{dN_\nu}{dE_\nu},$$

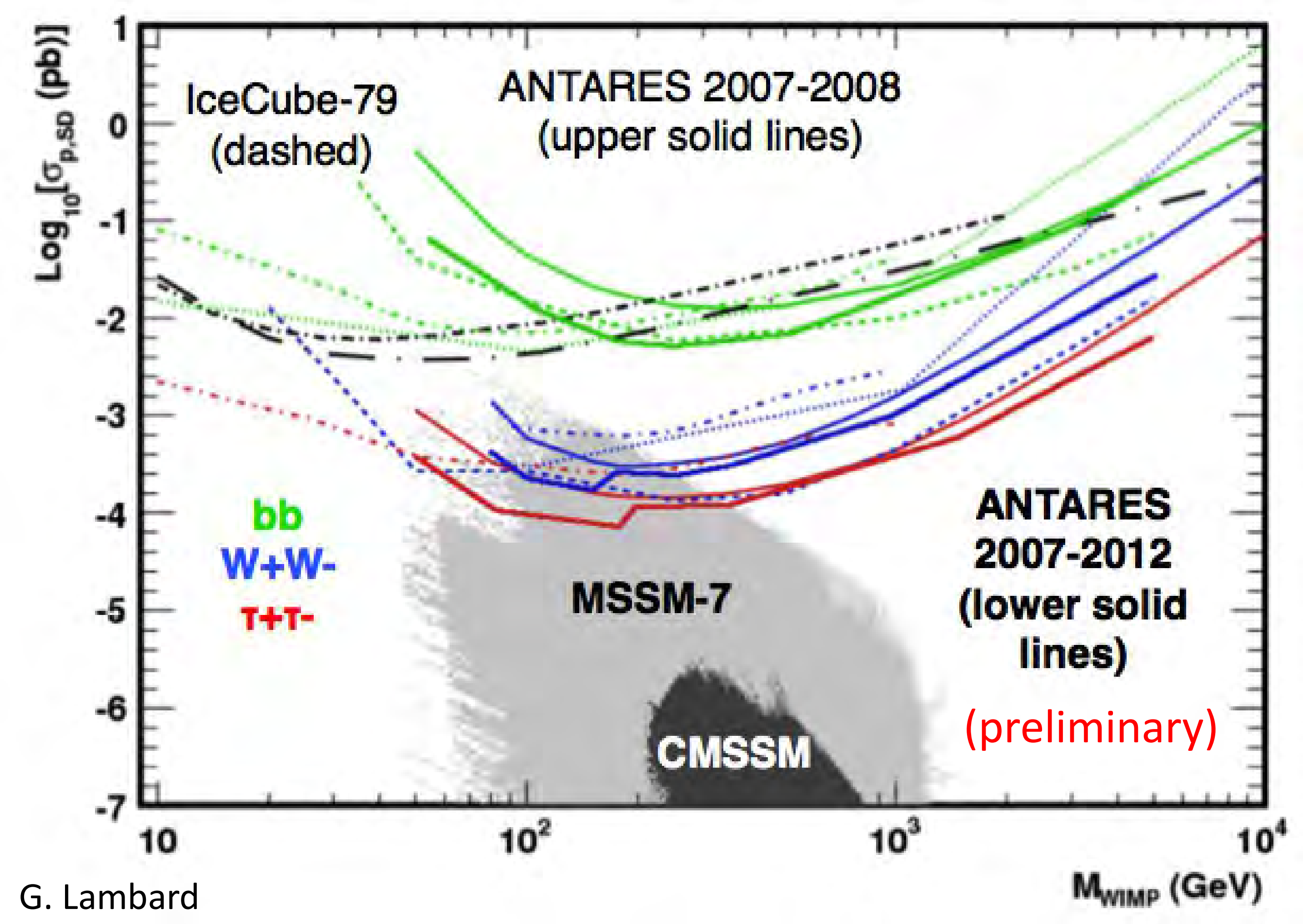
If we assume equilibrium between capture and annihilation in the Sun:

$$\Gamma \simeq \frac{C_\otimes}{2}.$$

where the capture rate can be expressed as:

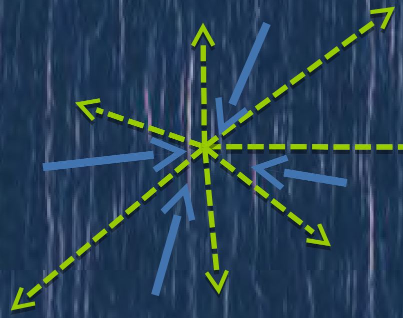
$$C_\otimes \simeq 3.35 \times 10^{18}\mathrm{s}^{-1} \times \left(\frac{\rho_{\mathrm{local}}}{0.3\, GeV \cdot cm^{-3}}\right) \times \\ \times \left(\frac{270\,\mathrm{km}\cdot\mathrm{s}^{-1}}{v_{\mathrm{local}}}\right) \times \left(\frac{\sigma_{H,SD}}{10^{-6}\,\mathrm{pb}}\right) \times \left(\frac{TeV}{M_{\mathrm{WIMP}}}\right)^2,$$

Sun: limits on σ_{SD}



G. Lambard

Galactic Centre



WIMPs

$\nu_{e,\,\nu\mu,\,\nu\tau}$

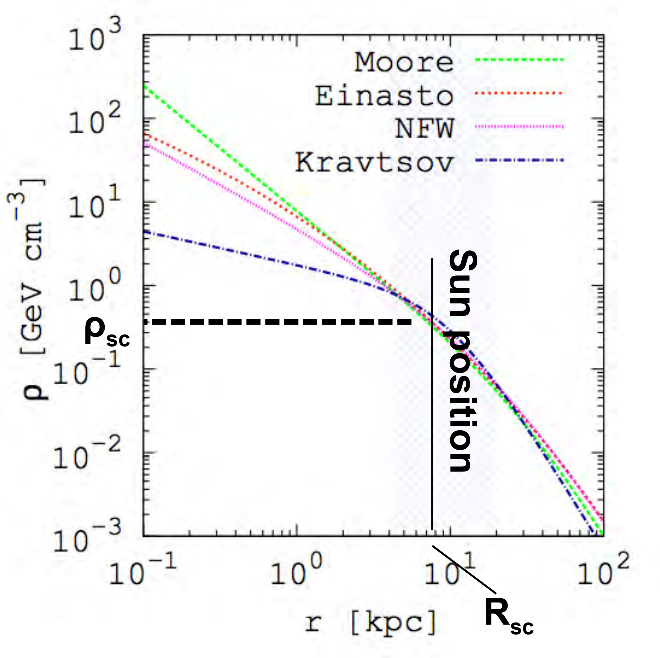
ν oscillations in the vacuum

ν can propagate with a minimum of astrophysical uncertainties

Galactic Center

Earth

- WIMPs self-annihilate according to $<\sigma_{Av}>$ (halo model-dependent)



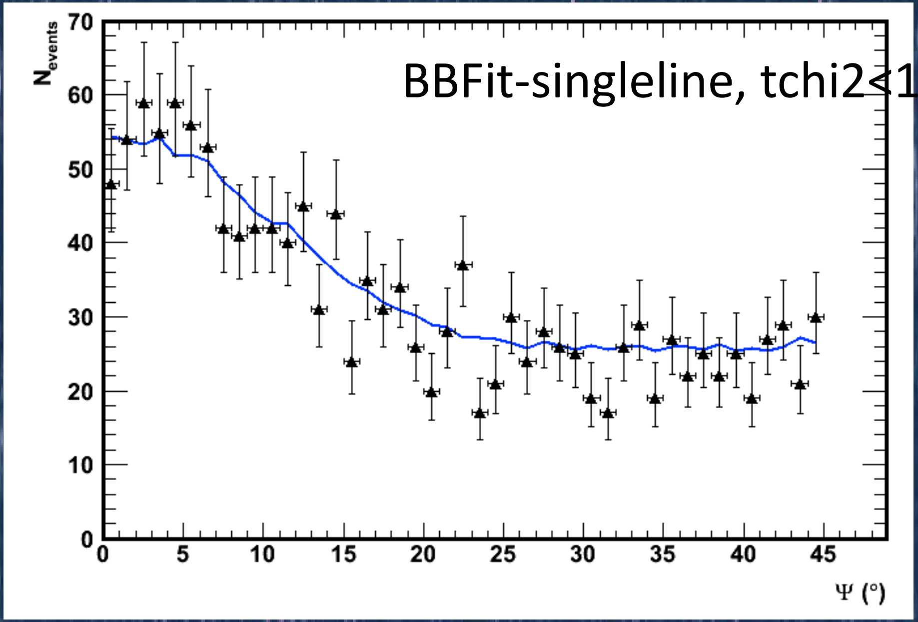
$$\frac{d\Phi_\nu}{dE_\nu}(E_\nu,\Delta\Psi) = \Phi^{PP}(E_\nu) \times J(\Delta\Psi)$$

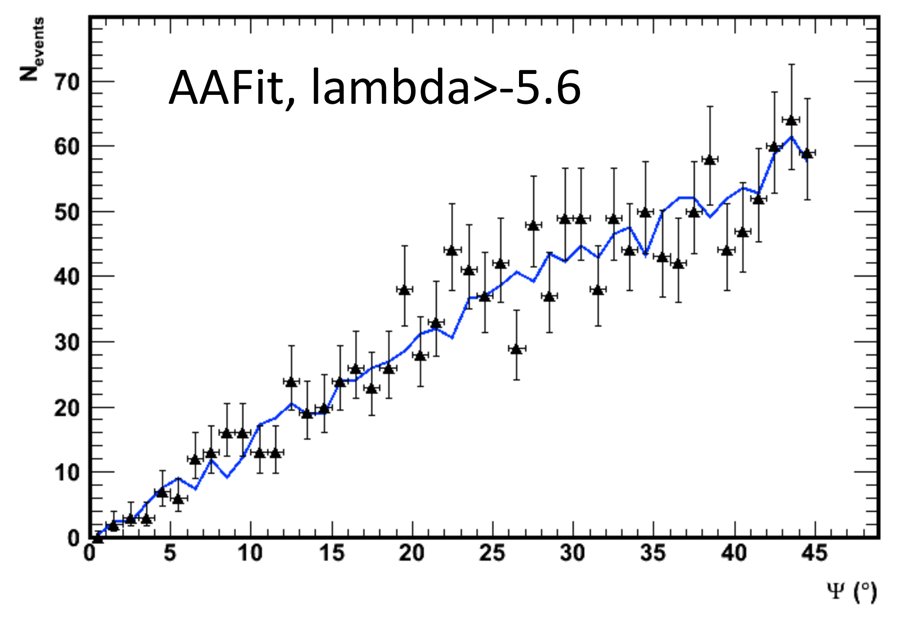
where

$$\Phi^{PP} \equiv \frac{1}{4\pi}\frac{<\sigma v>}{2M^2_{WIMP}}\frac{dN_\nu}{dE_\nu}$$

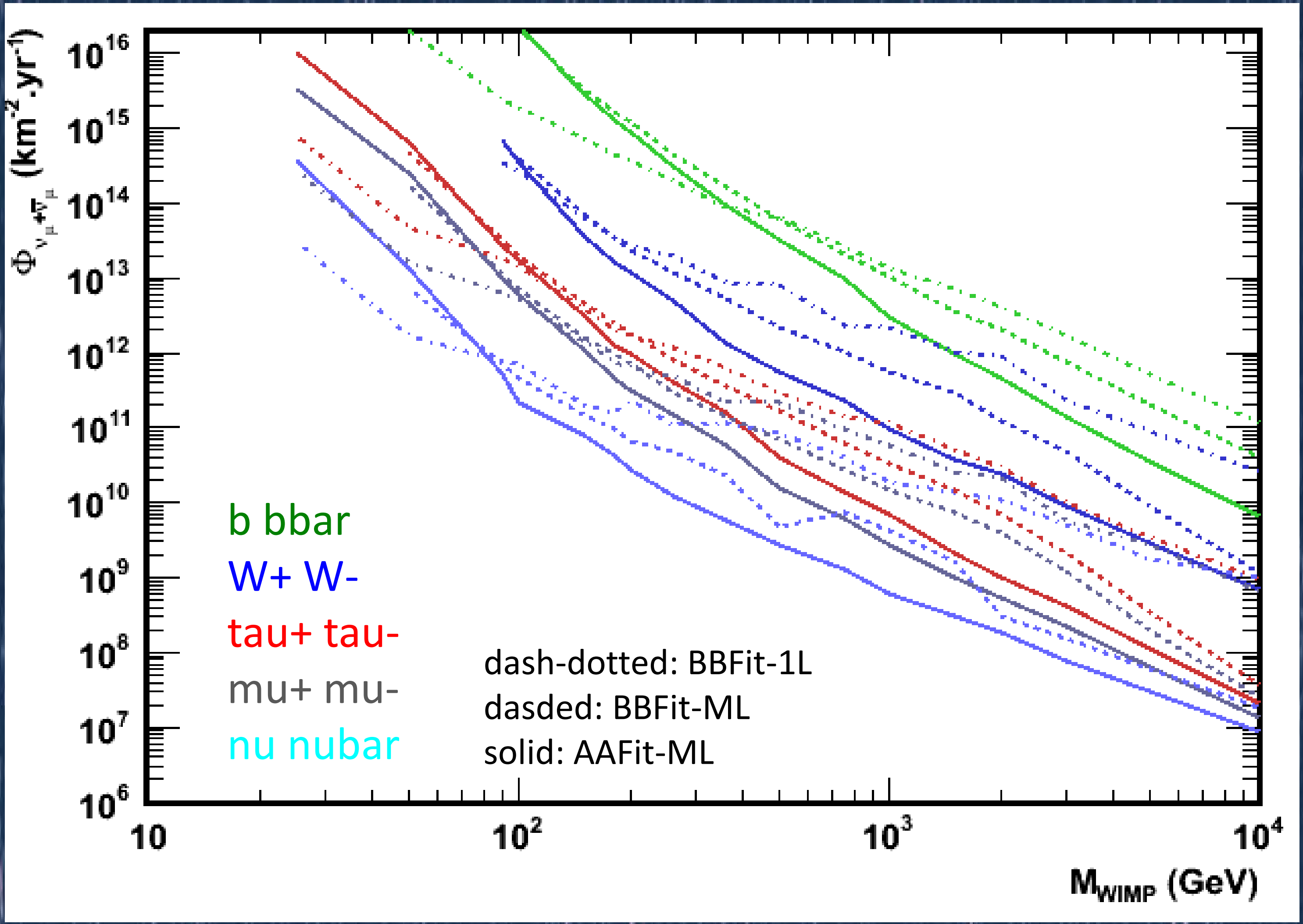
$$J(\Delta\Psi) = \int_{\Delta\Psi}\int \rho^2_{DM}(l,\Psi)\,dl\,d\Psi$$

GC: unblinding data

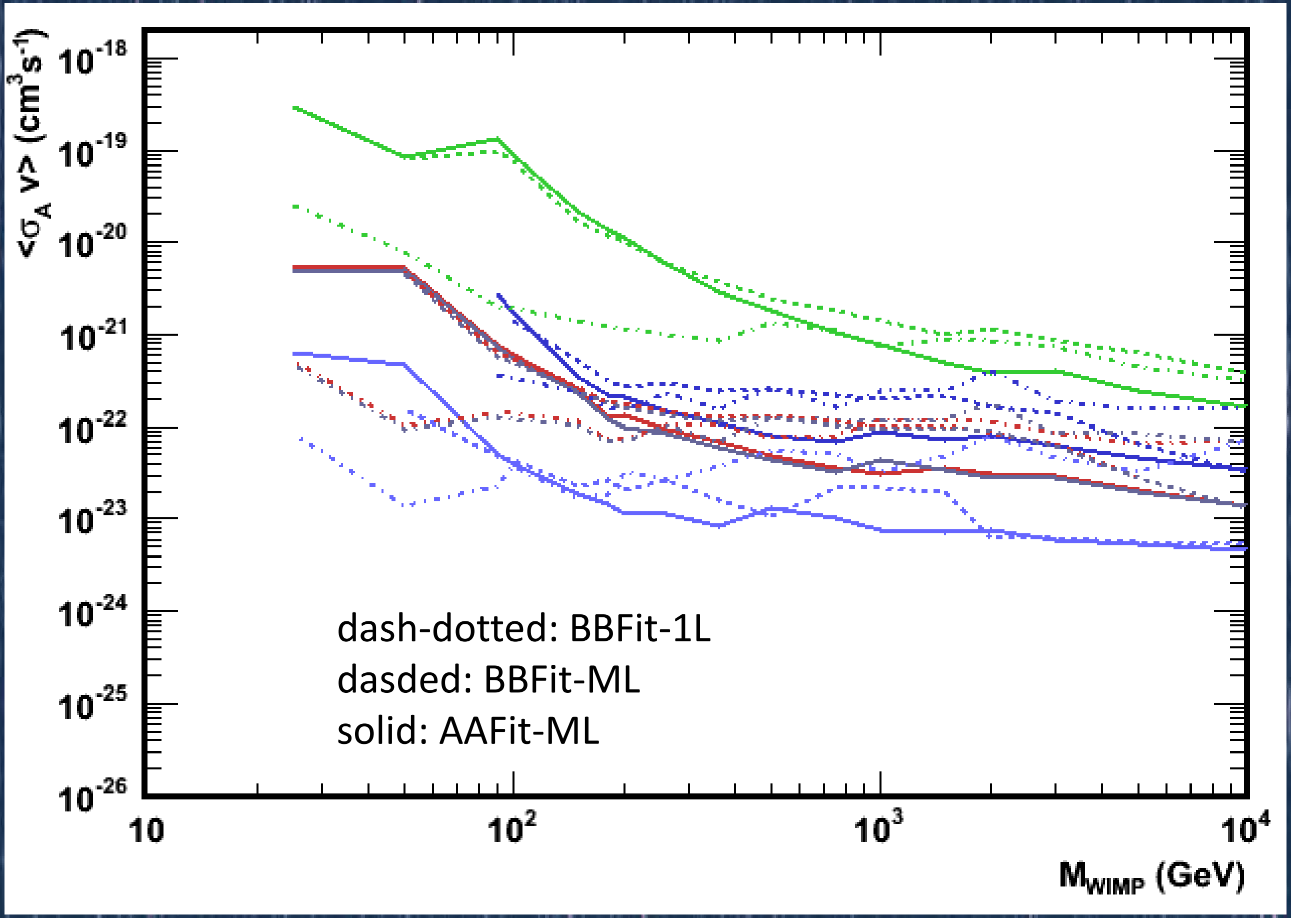




GC: limits on the flux



GC: <σv> for different channels

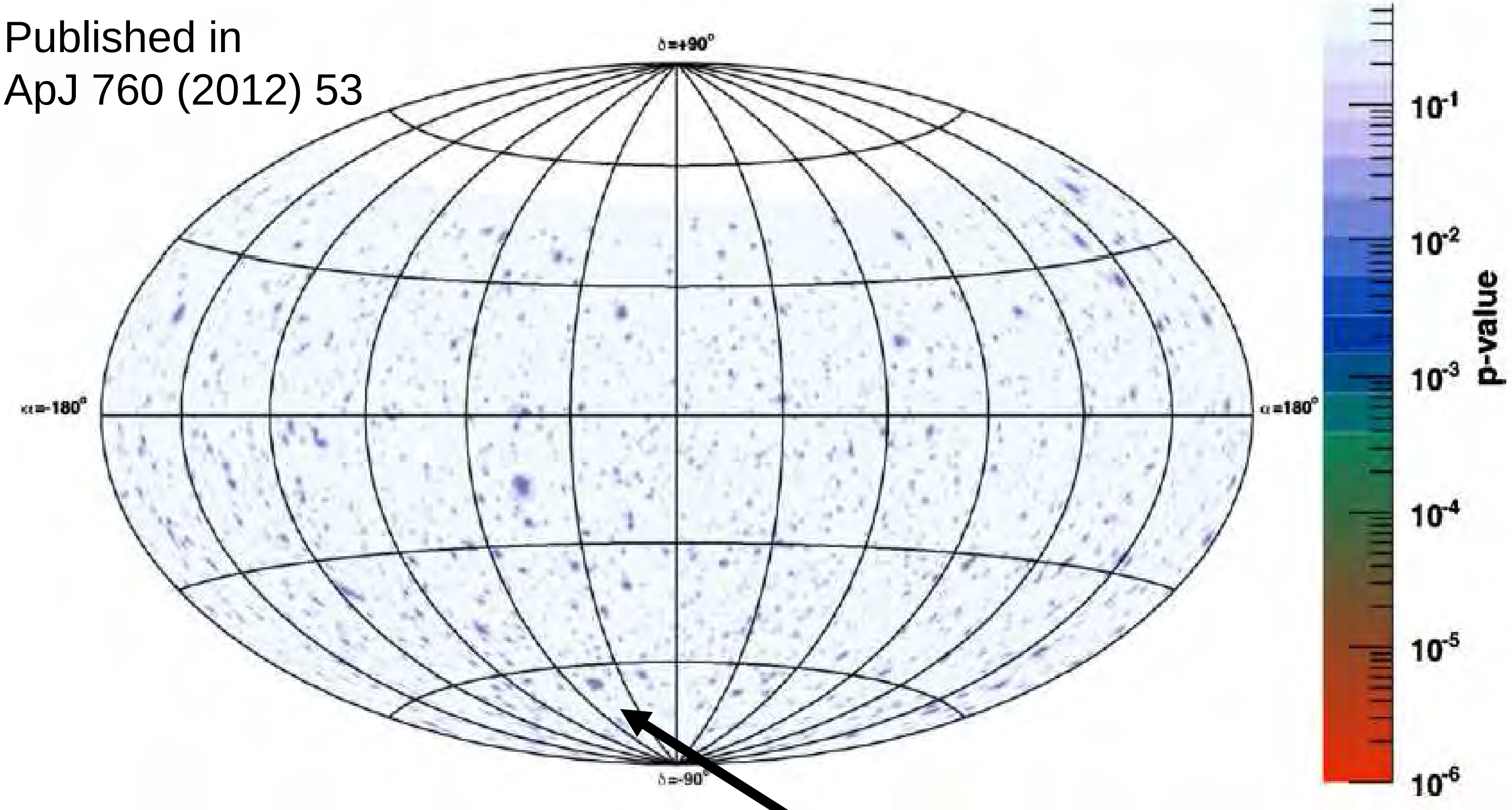


dash-dotted: BBFit-1L
dasded: BBFit-ML
solid: AAFit-ML

b bbar
W+ W-
tau+ tau-
mu+ mu-
nu nubar

Full-Sky Point Source Search

Published in
ApJ 760 (2012) 53



ANTARES 2007-2010 data
~3000 neutrino candidates (85 % purity)
Angular resolution 0.5 +/- 0.1 degrees

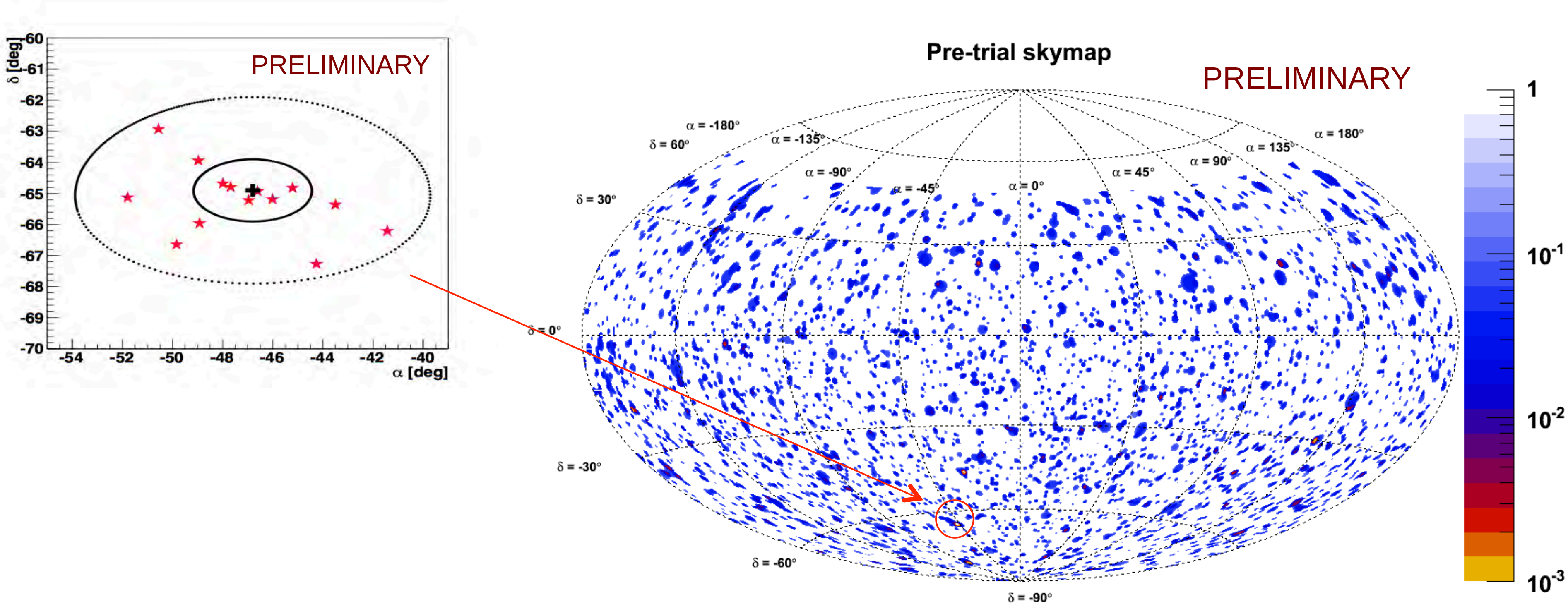
No statistical significant signal
Best cluster with 2.2σ
at (-46.5°, -65.0°)

Search for neutrino point sources III

❖ New updated search 2007-2012 (1340 days)

PRELIMINARY !

- 5516 neutrino candidates (90 % of which being better reconstructed than 1º)
- No significant excess
- Same most significant cluster with 6 additional events: p-value = 2.1% (2.3 σ)
  Compatible with background hypothesis

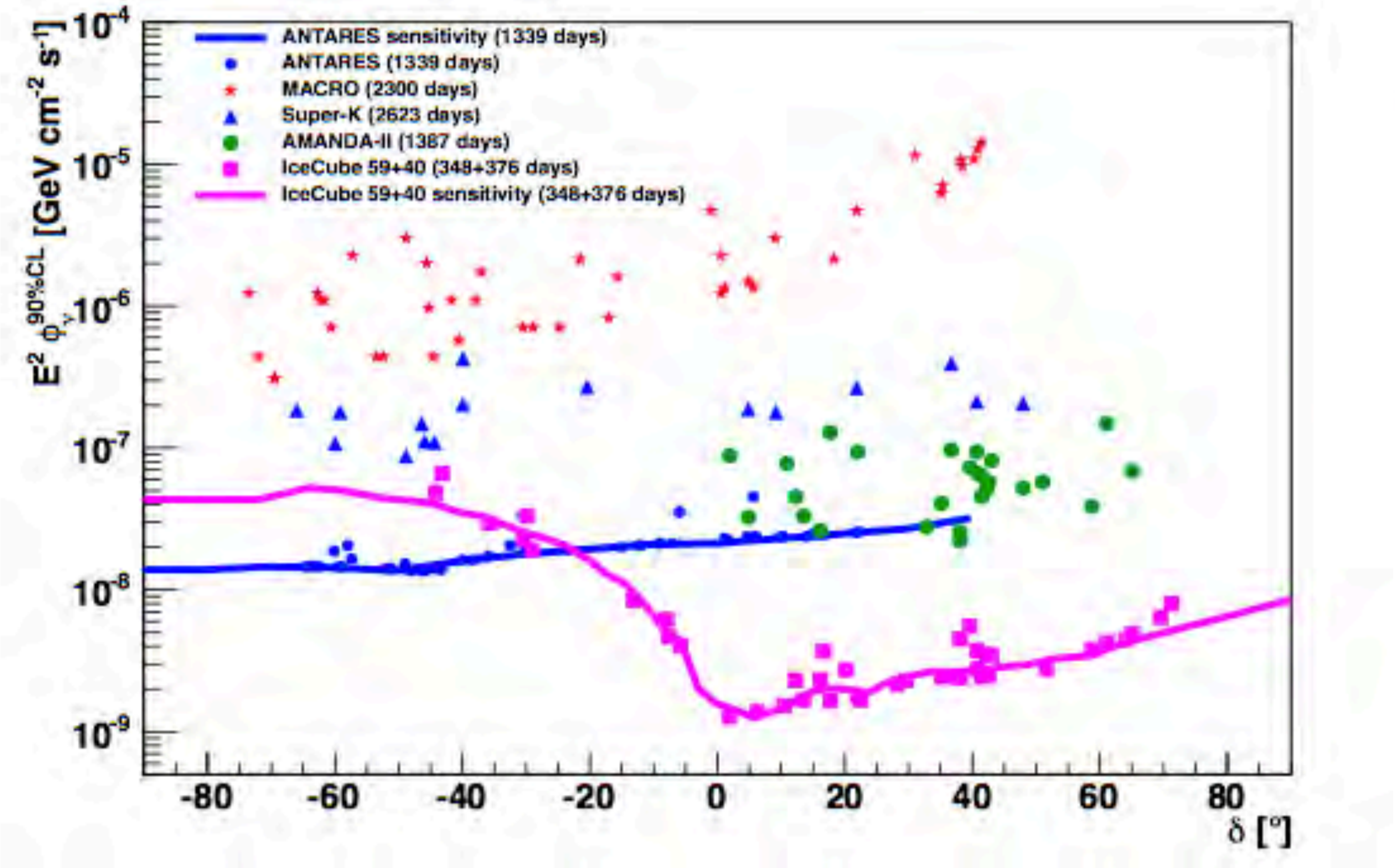


Pre-trial skymap

Equatorial coordinates

Search for neutrino point sources IV

Most stringent limits for a large part of the Southern Sky in TeV region



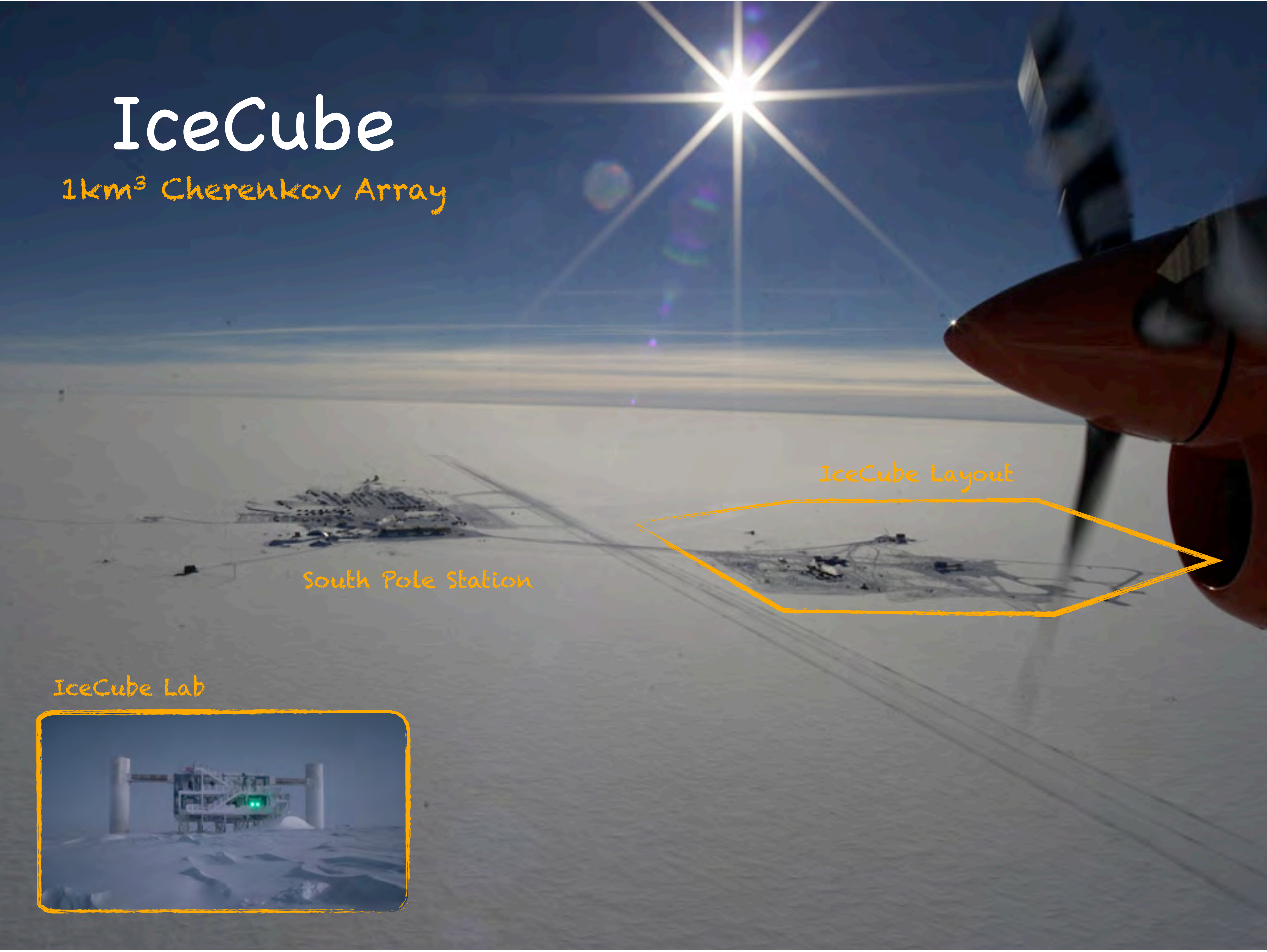
Dedicated studies for extended sources (RXJ1713, Vela X) → limits

Expect further improvement including showers (work in progress)

☞ Talk by S. Schulte ID 0425

IceCube

1km^3 Cherenkov Array



IceCube: constructed in 7 seasons

IceCube-1/IceCube-9
IceCube-22
IceCube-40
IceCube-59
IceCube-79
IceCube-86 (1st year), IceCube-86 (2nd year)

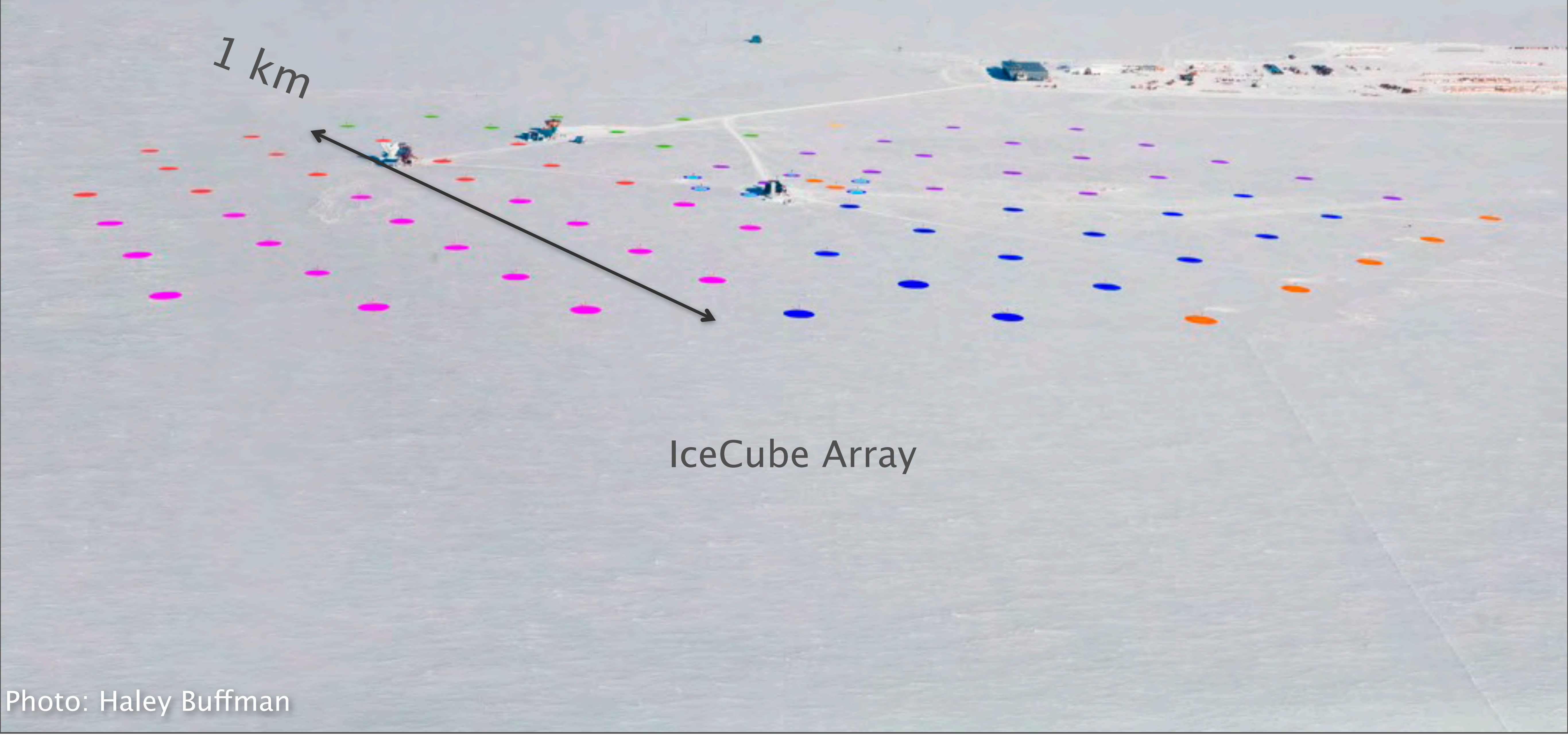


Photo: Haley Buffman

Water vs Ice

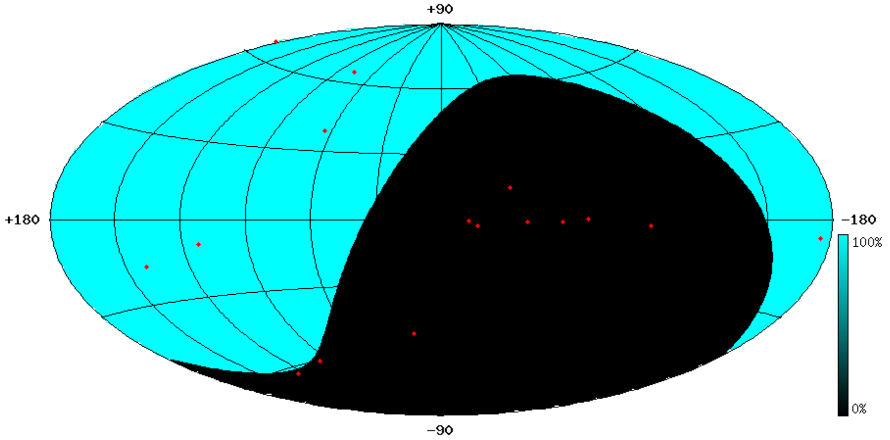
- Very large volumes of medium transparent to Cherenkov light are needed:
  - Ocean, lakes…
  - Antarctic ice
- Advantages of <u>oceans</u>:
  - Larger scattering length → better angular resolution
  - Weaker depth-dependence of optical parameters
  - Possibility of recovery
  - Changeable detector geometry

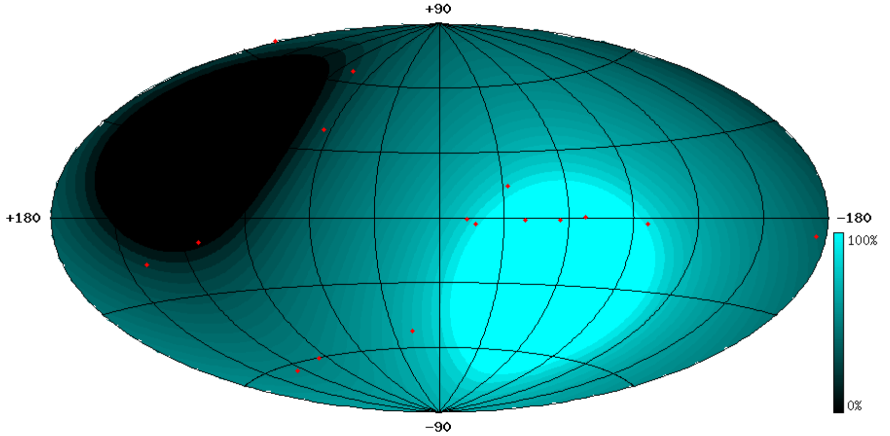
- Advantages of <u>ice</u>:
  - Larger absorption length
  - No bioluminescence, no 40K background, no biofouling
  - Easier deployment
  - Lower risk of point-failure
- Anyway, a detector in the Northern Hemisphere in necessary for complete sky coverage (Galactic Center!), and it is only feasible in the ocean.

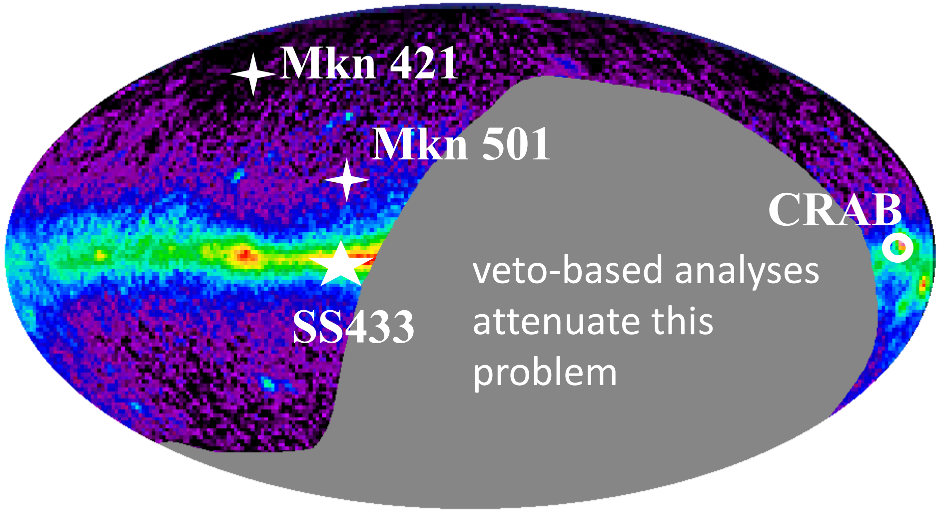
Regions of the sky observed by NTs

IceCube (South Pole)
(ang. res.: 0.6°)

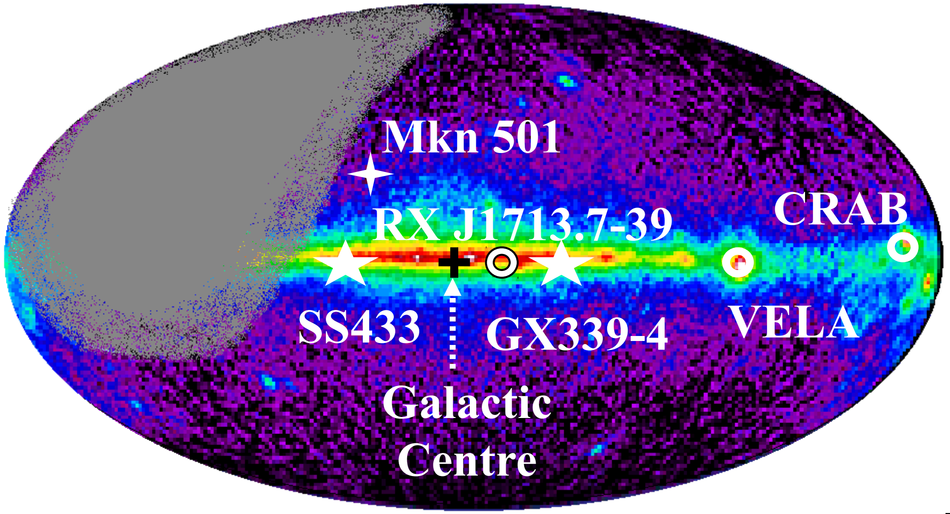
ANTARES (43° North)
(ang. res.: ~0.3°)

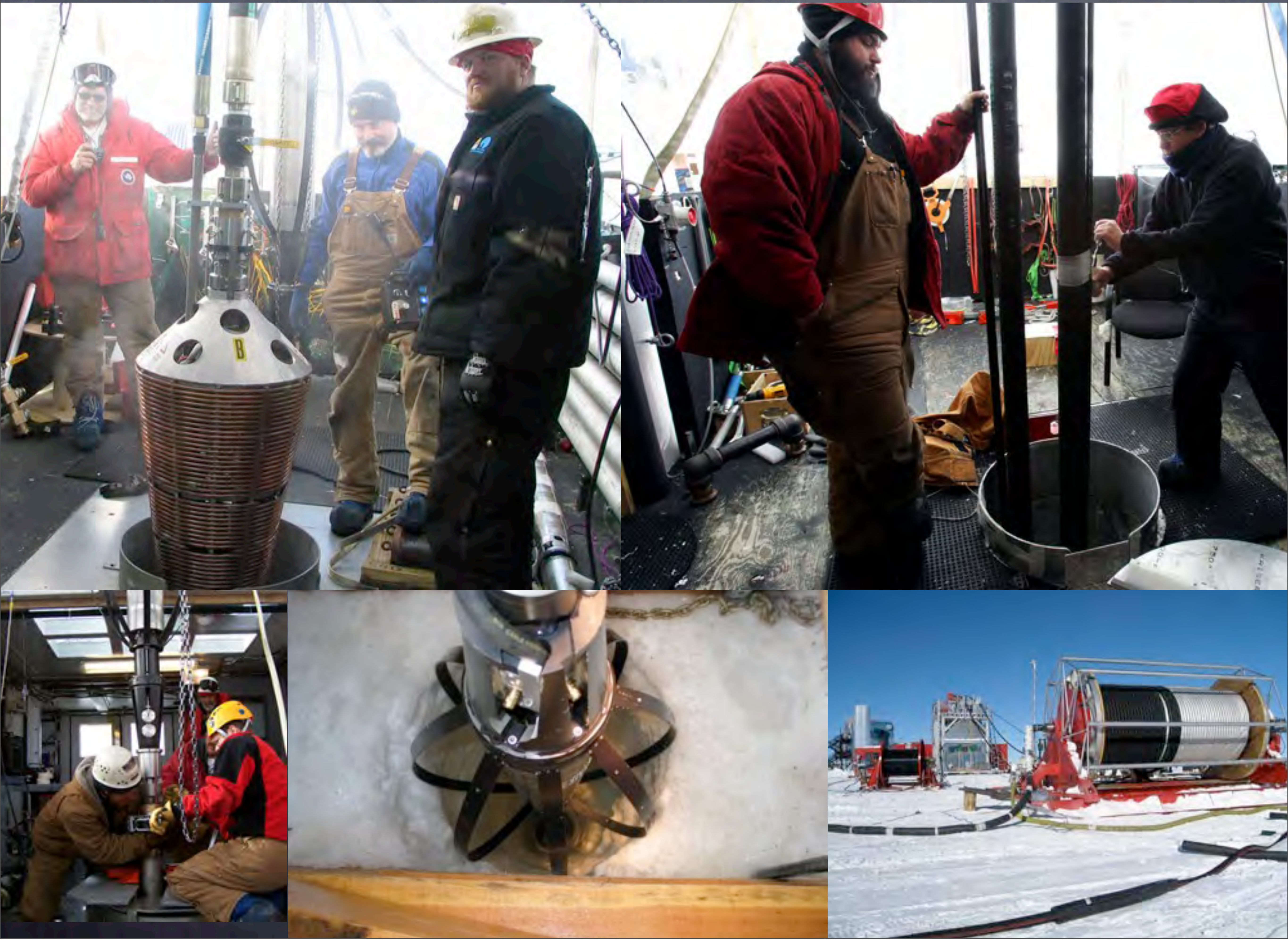






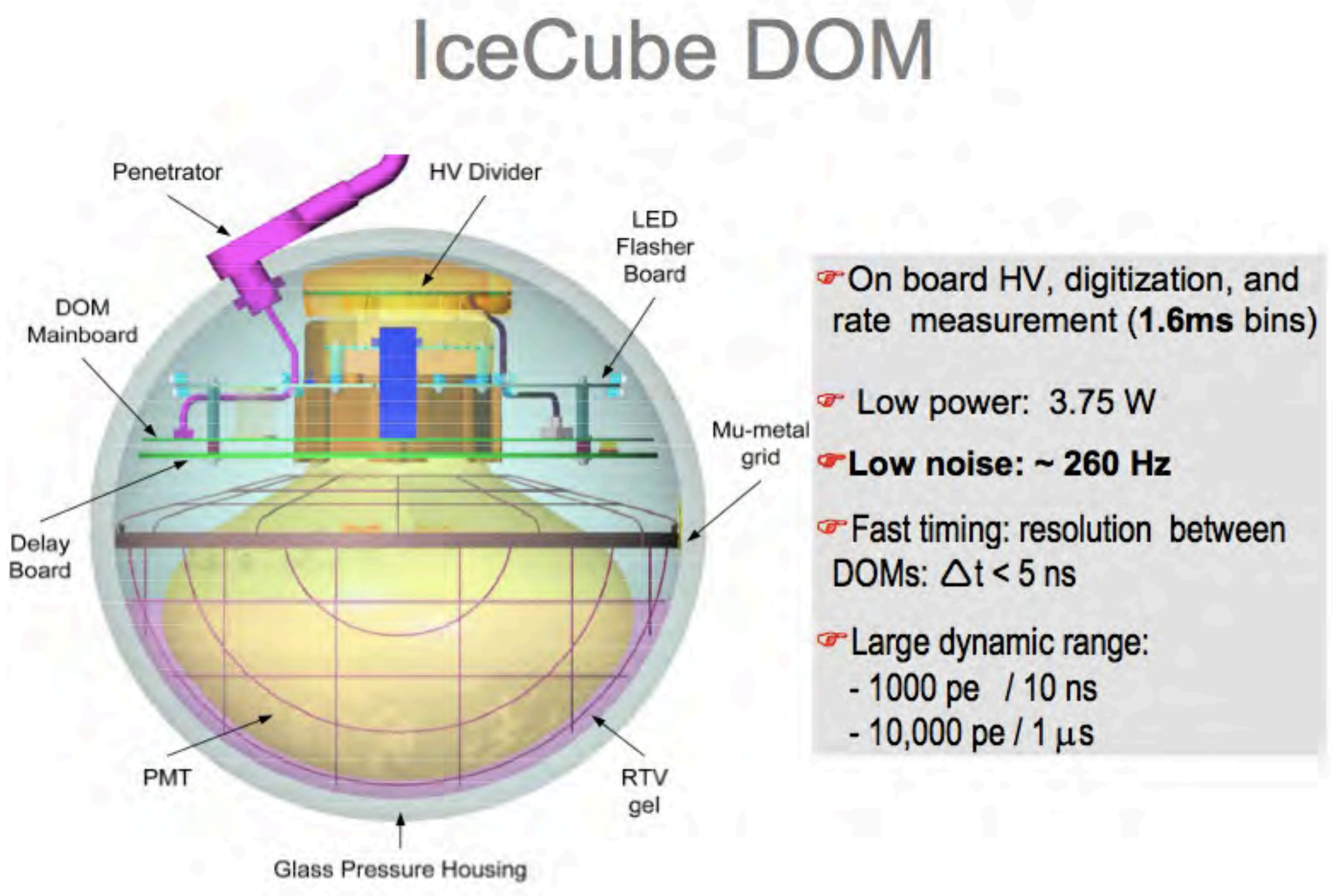
veto-based analyses attenuate this problem




B

5) Neutrino telescopes: core collapse SN

How does it work (*first proposed by Halzen, Jacobsen & Zas, astro-ph/9512080)*

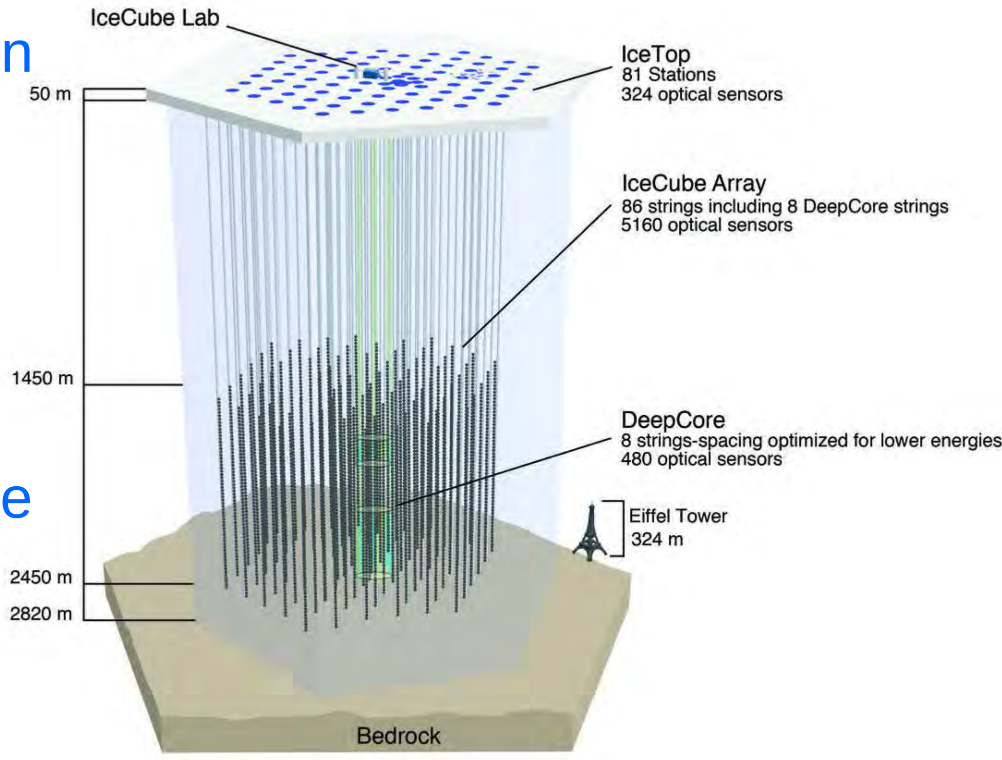


IceCube DOM

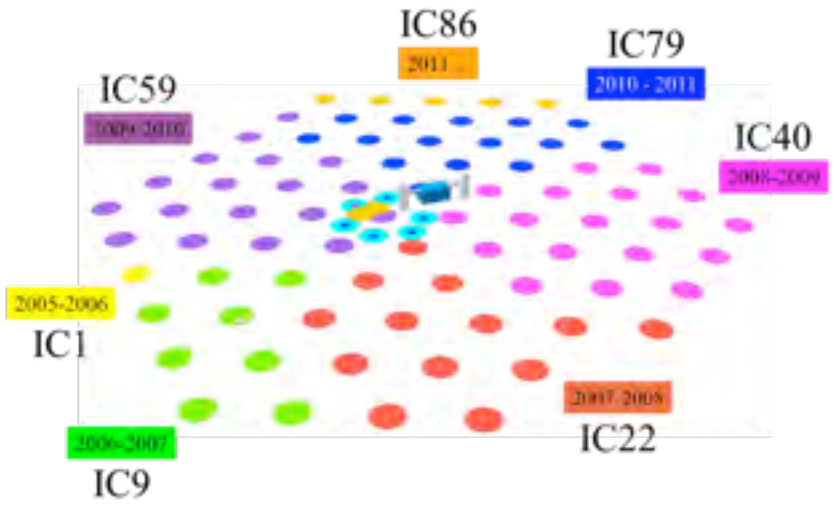
- On board HV, digitization, and rate measurement (**1.6ms** bins)
- Low power: 3.75 W
- **Low noise: ~ 260 Hz**
- Fast timing: resolution between DOMs: $\Delta t < 5$ ns
- Large dynamic range:
  - 1000 pe / 10 ns
  - 10,000 pe / 1 μs

IceCube

- 1 km^3 neutrino detector
  - Detects the Cherenkov light from charged particles produced in high-energy neutrino interactions
- 5,160 digital optical modules (DOMs) on 86 vertical strings
  - 25.4 cm phototube
  - Autonomous data acquisition
- IceTop 1 km^2 surface array
  - 162 ice-filled tanks
- Completed, Dec. 2010
- Reliability is excellent
  - 98.5% of channels are active
  - 2 DOMs failed in 2012
- Typical up-time 99%



The detector



~1 Gton instrumented volume

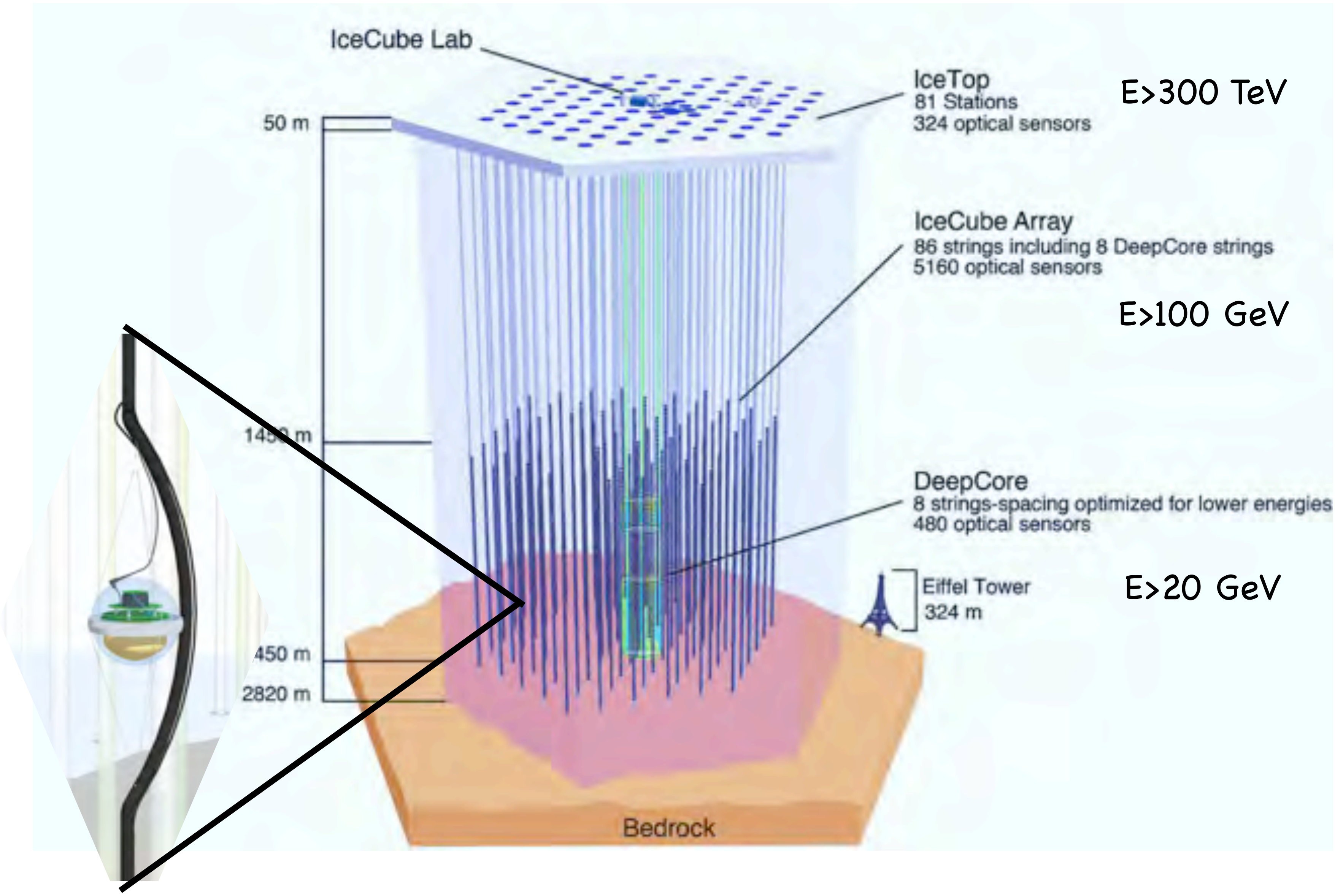
- Completed in December 2010
- >99% of DOMs survived installation
- Expect >97% operational in 2025

Digital Optical Module:

- 10inch PMT
- Electronic digitization
- Communication

DeepCore:

- High efficiency PMT
- ~4xIC sensor density
- 20 Mton detector



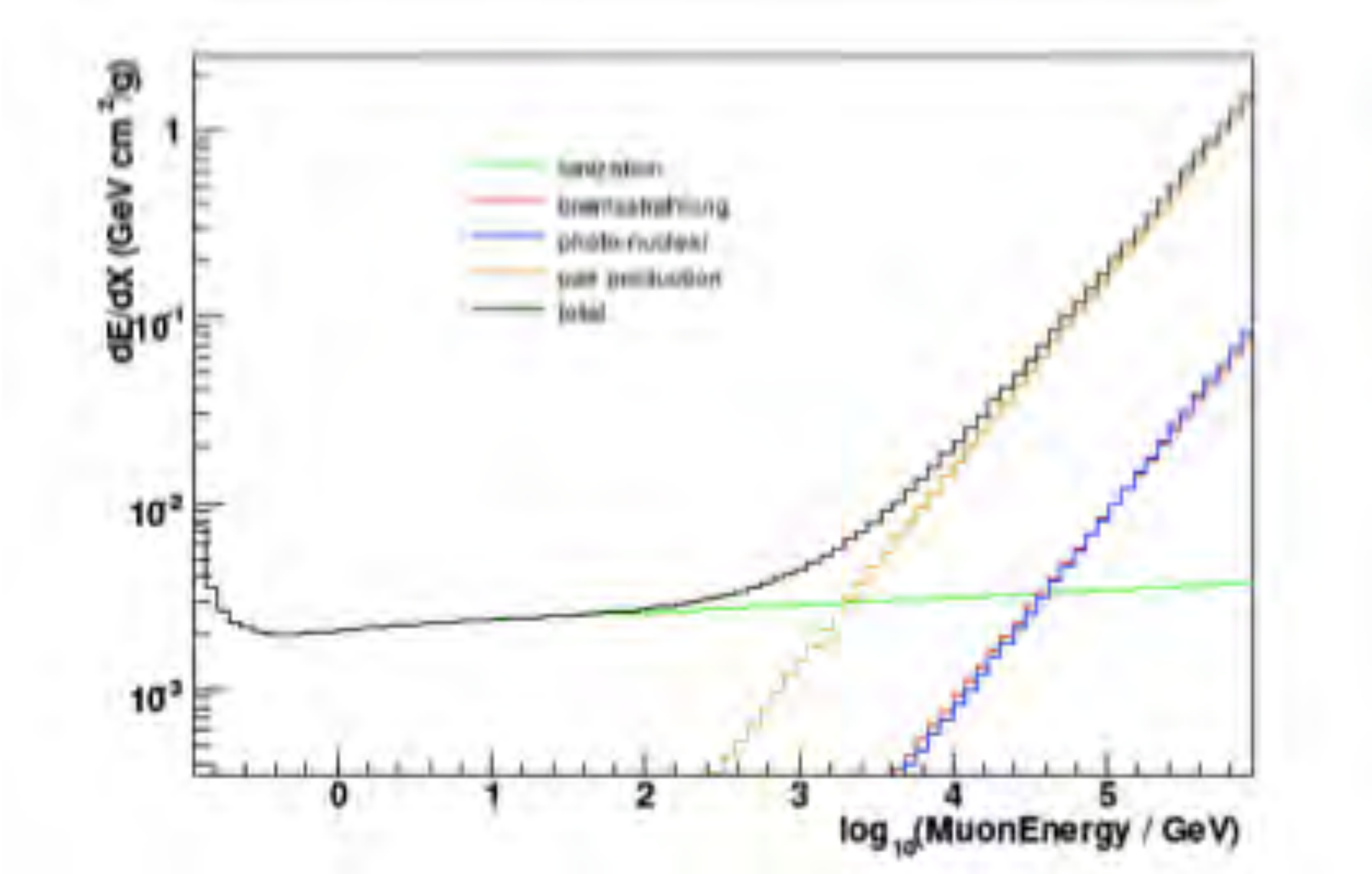
E>300 TeV

E>100 GeV

E>20 GeV

2) muons through matter

Energy loss: what is exactly emitting Cherenkov photons?

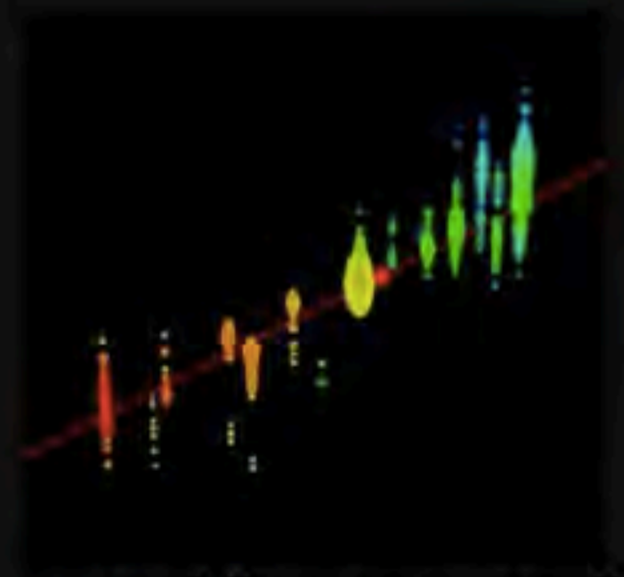


Eμ < 500 GeV ionization dominant (~ 2 MeV / cm)

Eμ > 500 GeV stochastic energy loss dominant

Neutrino signals

CC Muon Neutrino

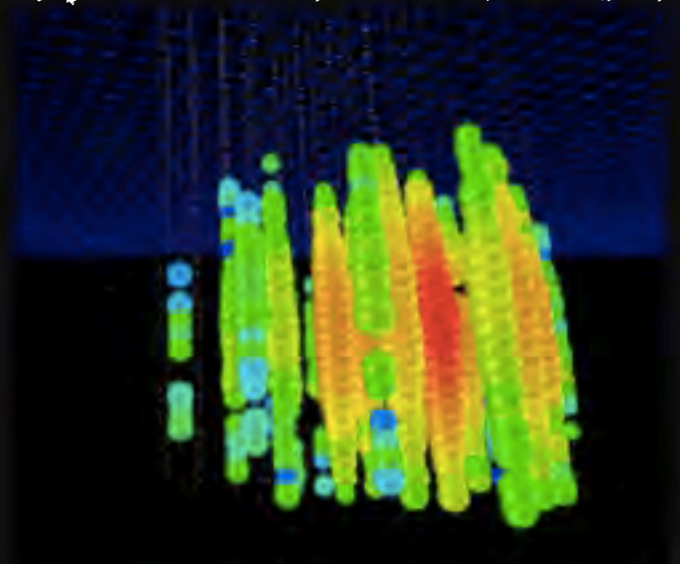


$$\nu_\mu + N \rightarrow \mu + X$$

track (data)

factor ~ 2 energy resolution
< 1° angular resolution (high energy)

NC/Electron Neutrino



$$\nu_e + N \rightarrow e + X$$

$$\nu_x + N \rightarrow \nu_x + X$$

cascade (data)

± 15% energy resolution
~ 10° angular resolution (>100TeV)

CC Tau Neutrino

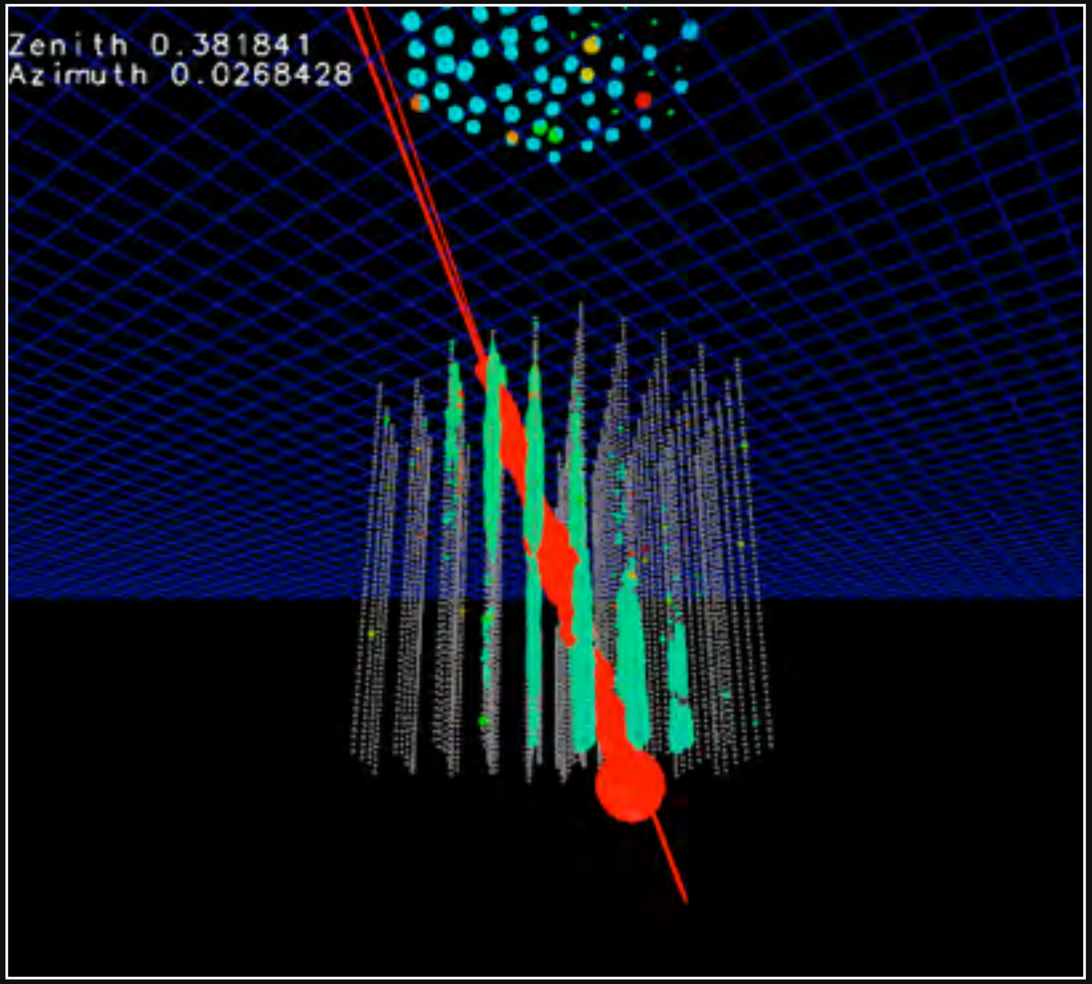
$$\nu_\tau + N \rightarrow \tau + X$$

"double-bang" and other signatures (simulation)

(not yet observed)

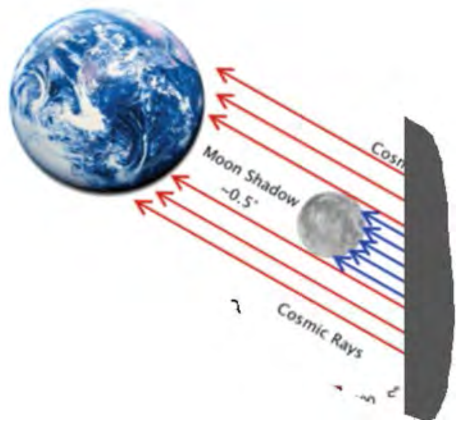
Backgrounds and Systematics

- **Backgrounds:**
  - Cosmic Ray Muons
  - Atmospheric Neutrinos
- **Largest Uncertainties:**
  - Optical Properties of Ice
  - Energy Scale Calibration
  - Neutral current / ν_e degeneracy



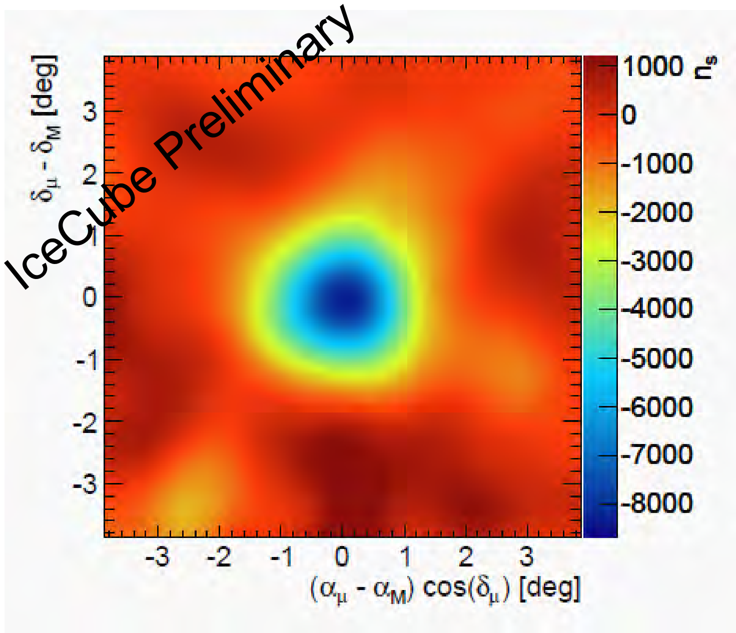
A bundle of muons from a CR interaction in the atmosphere (also observed in the "IceTop" surface array)

Calibration and performance



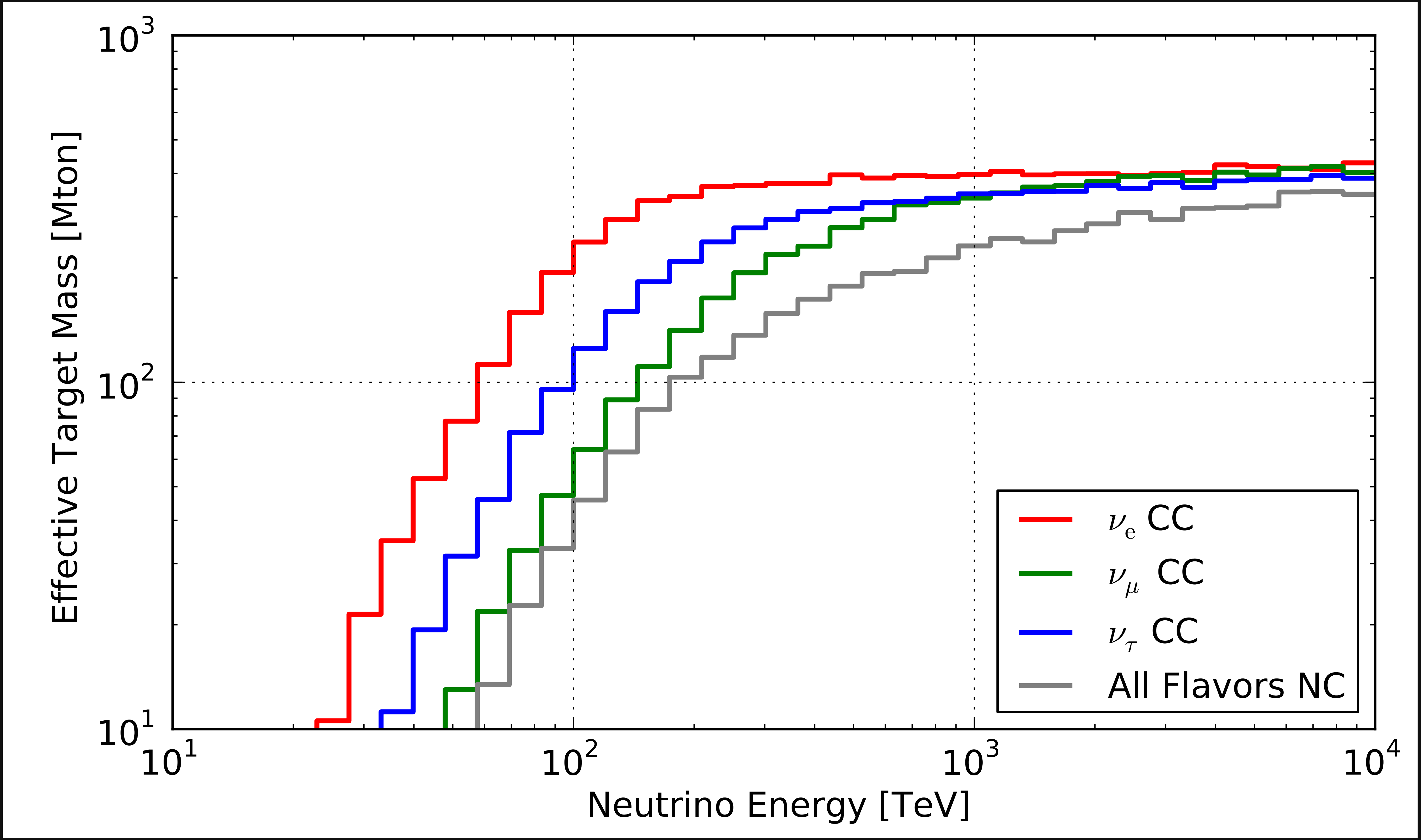
- Major systematic uncertainties:
  - Optical module efficiency
  - Optical properties of the ice
    - The ice is anisotropic! (Paper 0580)
- Studied with on-DOM light sources (LEDs), deployed 337 nm N_2 lasers, and cosmic-ray muons
- The moon is an anti-source
  - blocks cosmic-rays
- Angular resolution at high energies better than 1^0
  - 0.5^0 at 100 TeV

IceCube, arXiv:1305.6811



Effective Volume / Target Mass

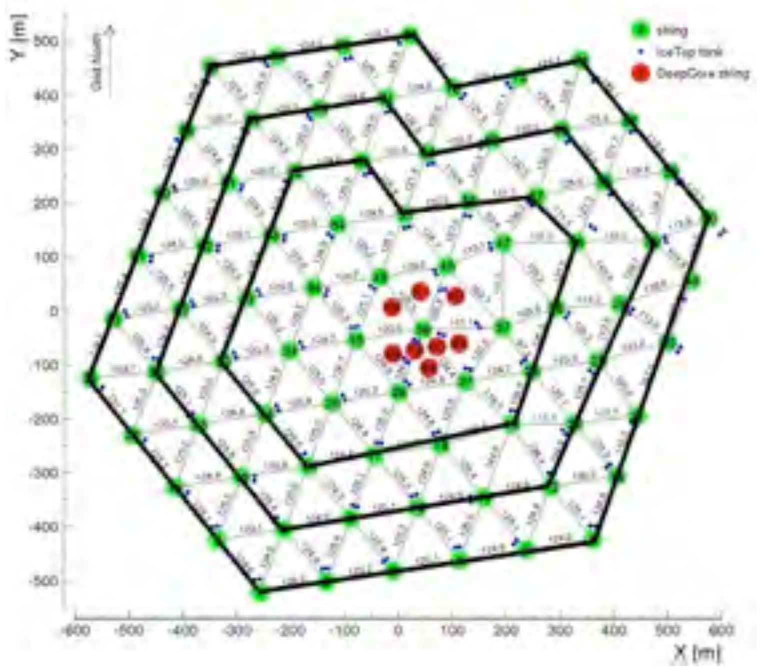
Fully efficient above 100 TeV for CC electron neutrinos
About 400 Mton effective target mass

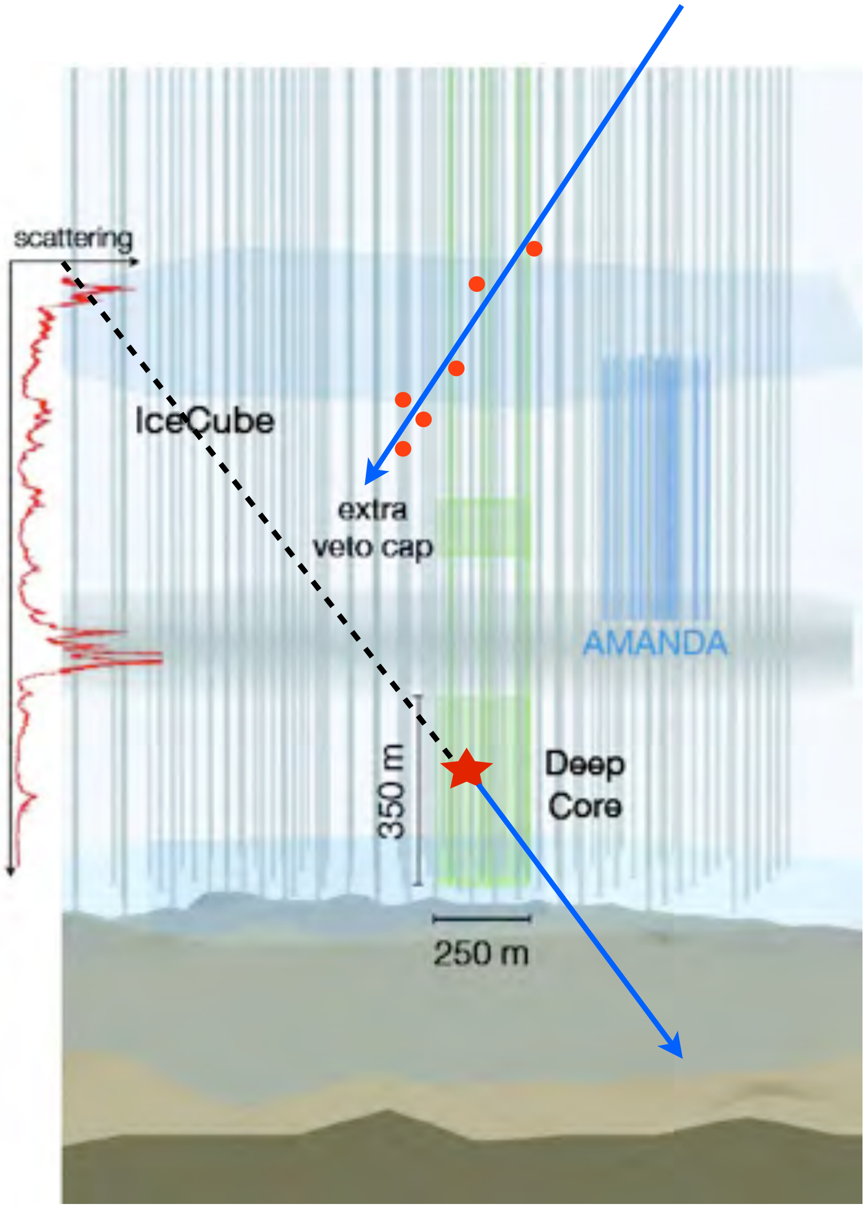


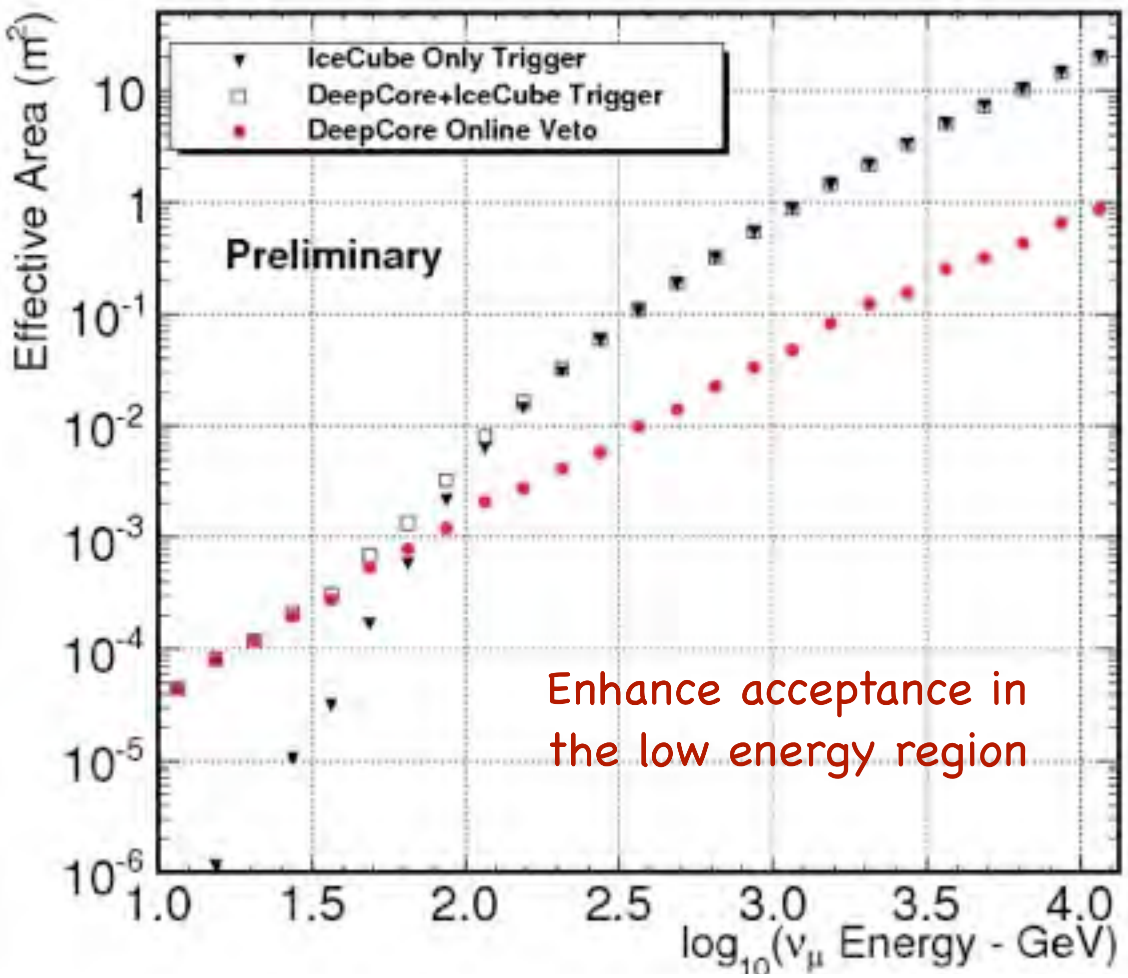
DeepCore

- Use IceCube outer strings as a veto:
    - 3 complete IC string layers around DeepCore (375m thick)
- Full sky sensitivity: access to southern hemisphere

installed during IC79

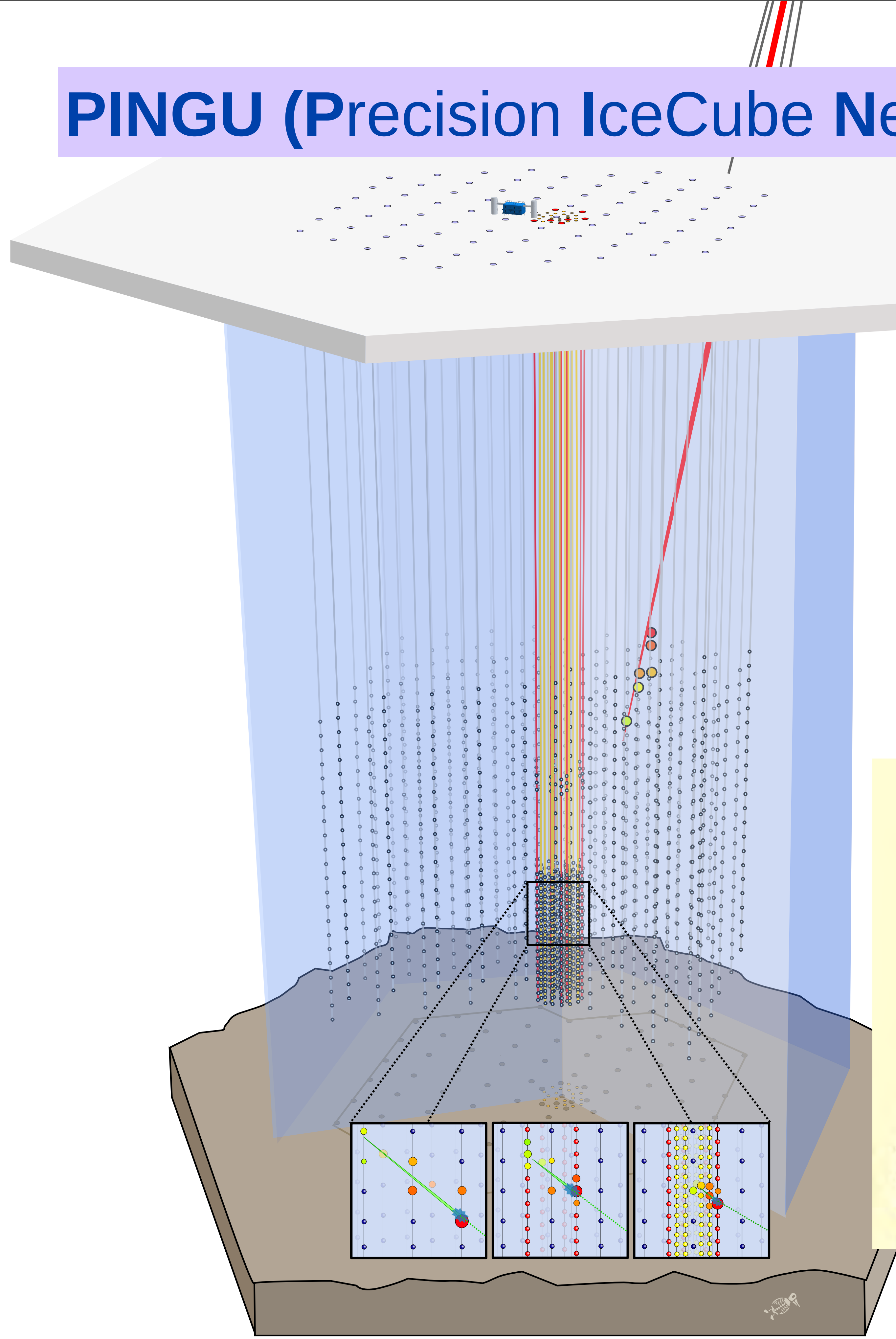






Enhance acceptance in the low energy region

PINGU (Precision IceCube Next Generation Upgrade)

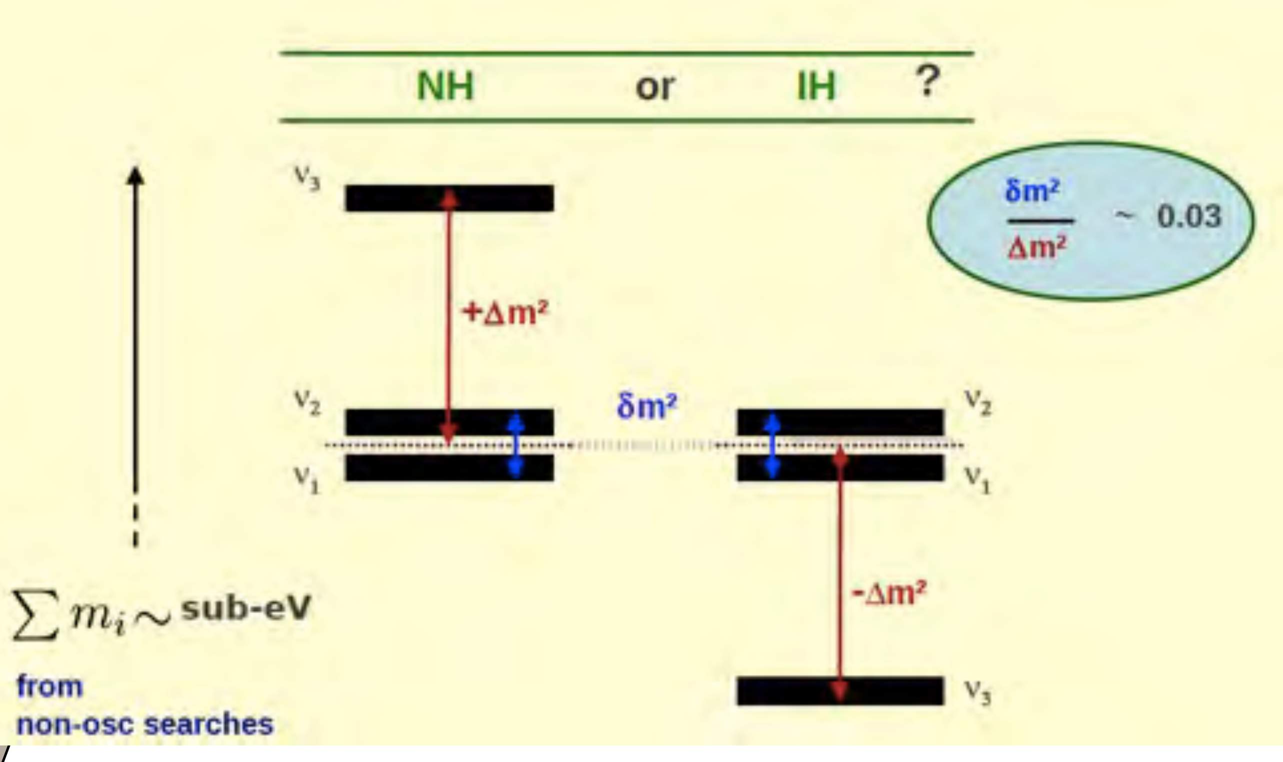


Under discussion:

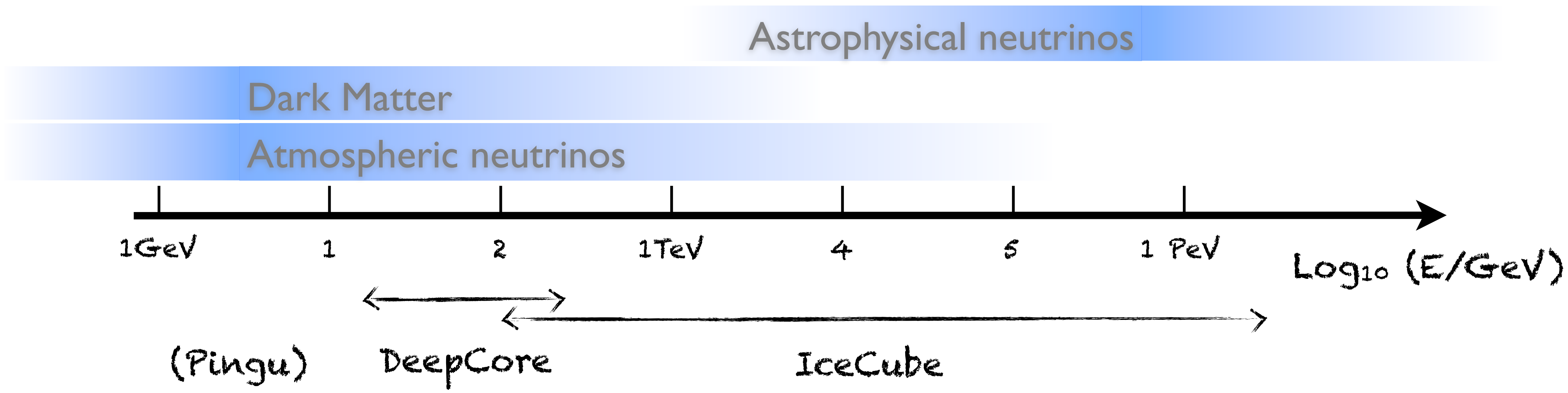
further extension of IceCube for the energy region from few GeV to 50 GeV

The primary physics goal of PINGU is the study of the **neutrino mass hierarchy**

What is “mass hierarchy”:



Dark Matter searches



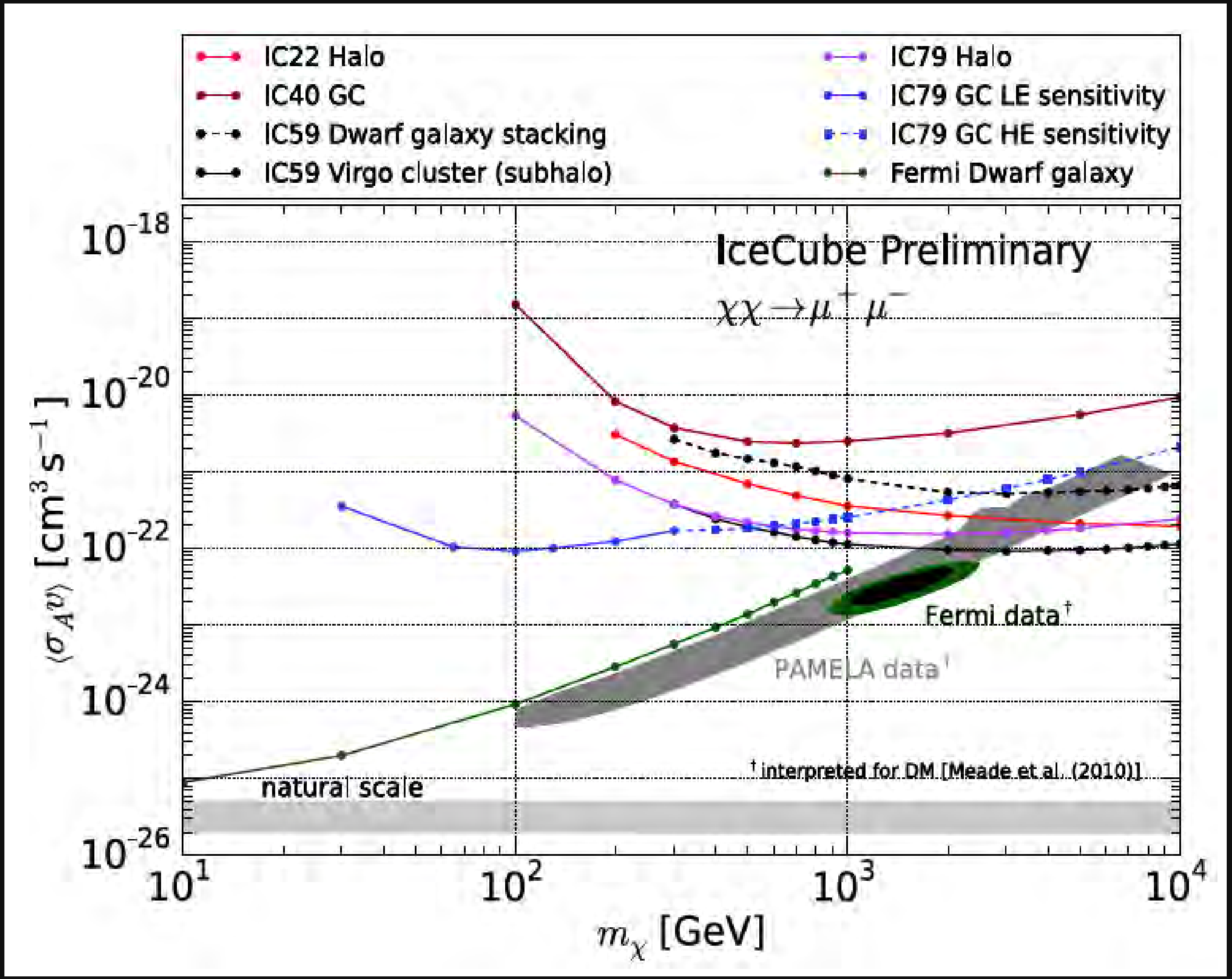
- WIMP searches are at the lower edge of current energy reach
- Look for neutrinos produced by DM annihilation into standard model particles
- Probe regions in the sky where DM might have gravitationally accumulated:
  - Earth (IC86 ongoing)
  - Sun (IC79 results, IC86 ongoing)
  - Galactic Center (IC79 results/ongoing, IC86 ongoing)
  - Galactic Halo (IC79 results, IC86 ongoing)
  - Dwarf spheroidal galaxies & clusters (IC59 results, IC79-86 ongoing)

Various Potential Dark Matter Signals

Various analyses looking at different source distributions

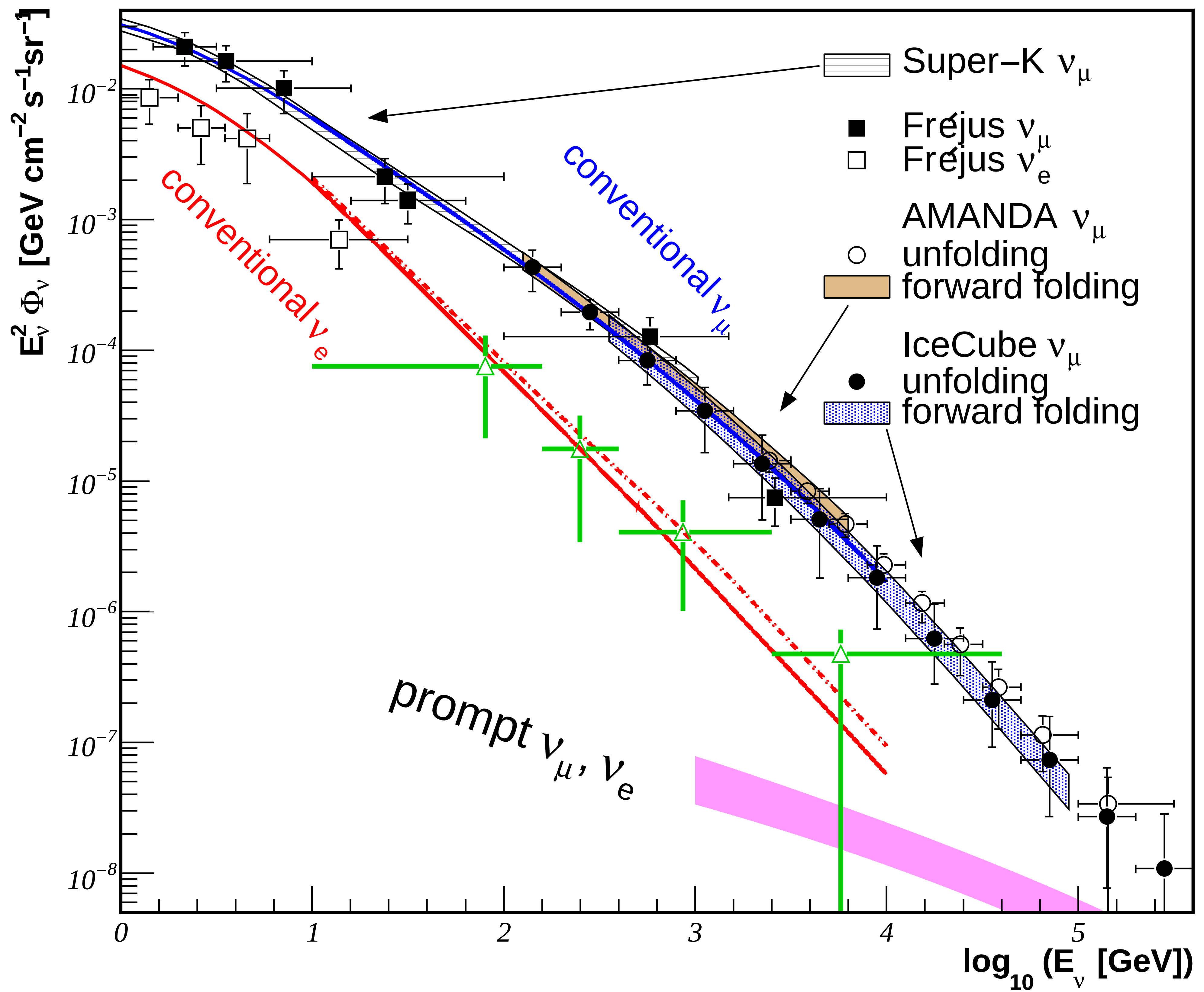
- **Galactic Halo:**
  - IC22 PRD 8 (2011) 022004
  - IC79 in preparation
- **Galactic Center:**
  - IC79 in preparation
- **Dwarf spheroids:**
  - IC59 PRD 88 (2013) 122001
- **Clusters of galaxies:**
  - IC59 PRD 88 (2013) 122001

high mass/light ratio



Atmospheric Neutrino Spectrum

Measured with IceCube in ν_μ and ν_e

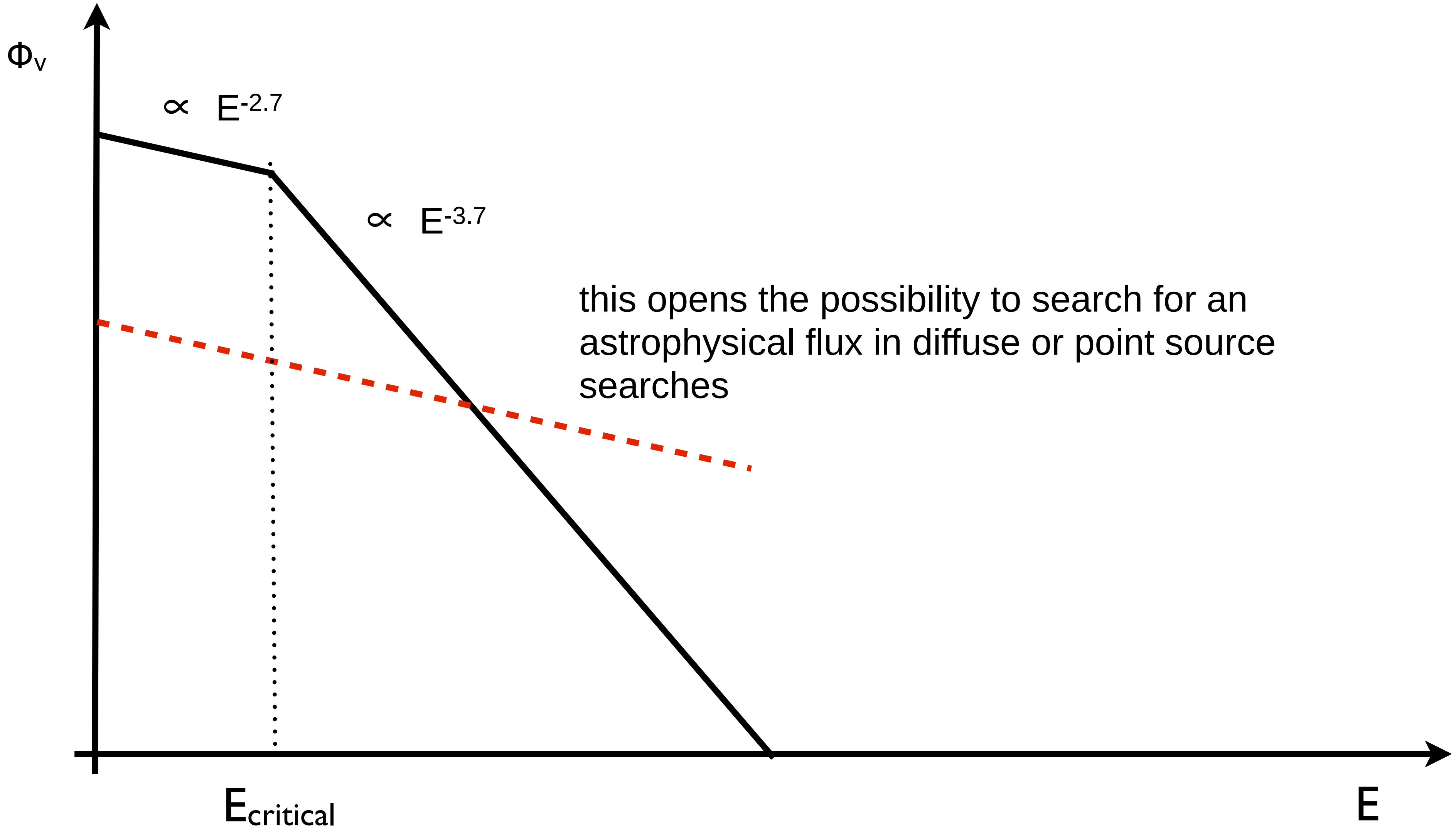


PRL 110 (2013) 151105

1) production of muons and neutrinos in the atmosphere

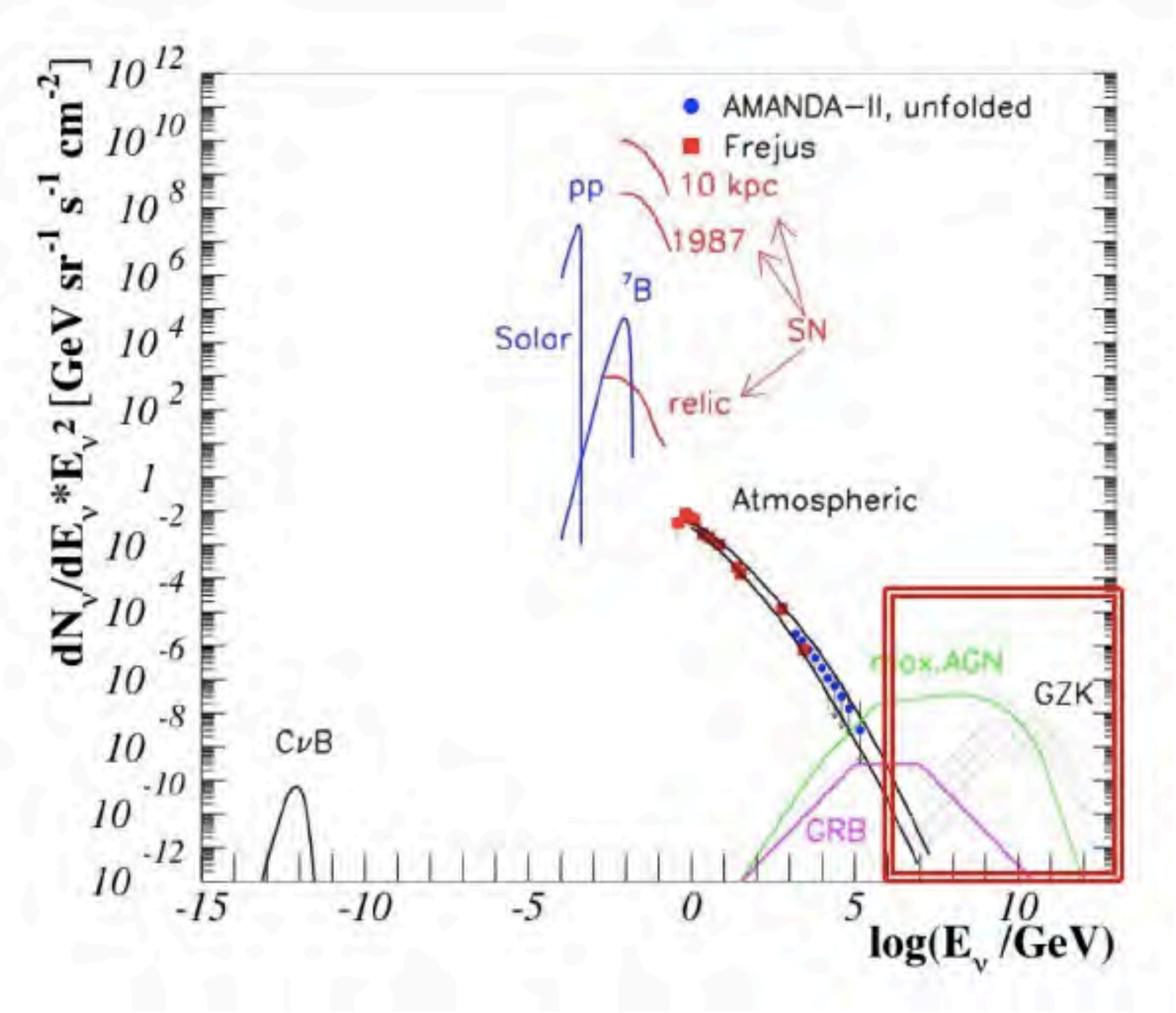
Critical energy depends also from matter density: in astrophysical environment density << atmospheric density.

Neutrino spectrum from astrophysical sites expected to be harder up to higher energies



this opens the possibility to search for an astrophysical flux in diffuse or point source searches

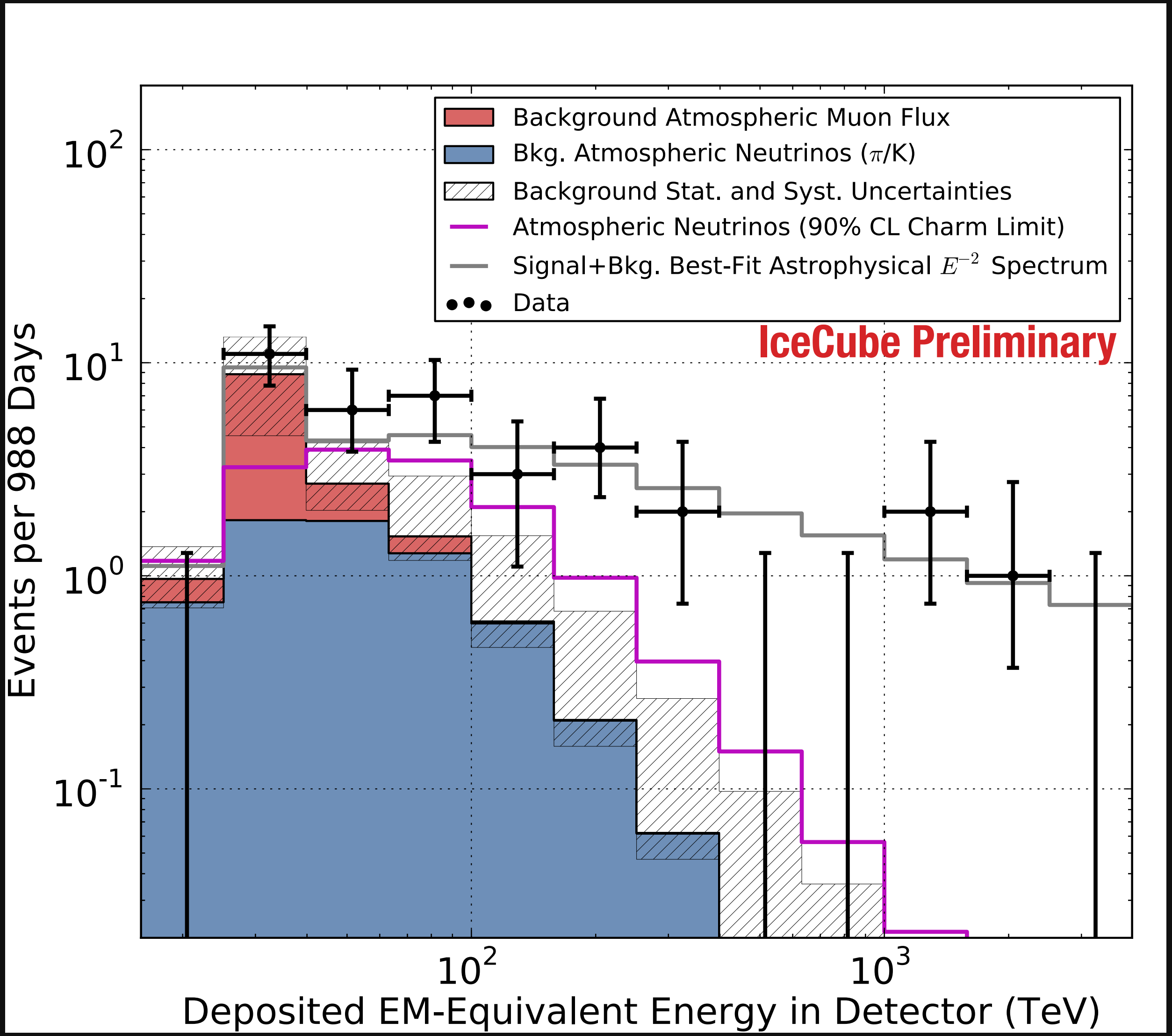
Neutrino telescopes: UHE cascades



Energy Spectrum

Compatible with benchmark E^{-2} astrophysical model

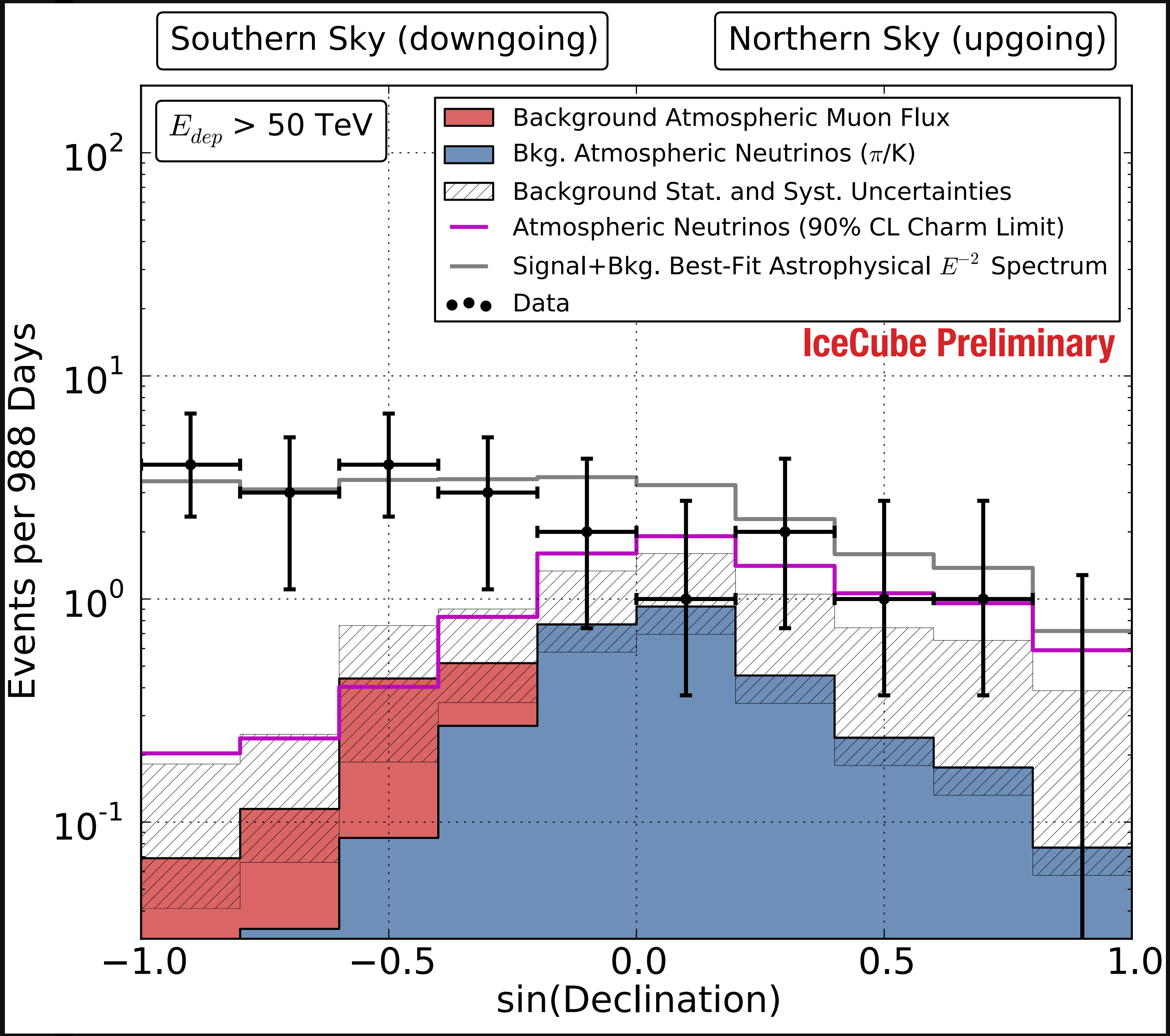
- **Harder than any expected atmospheric background**
- **Merges well into background at low energies**
- **Potential cutoff at about 2-5 PeV (or softer spectrum)**
- **Best fit (per-flavor flux):**
  - $0.95 \pm 0.3\ 10^{-8}\ E^{-2}$ GeV cm^{-2} s^{-1} sr^{-1}



Declination Distribution

Or: “zenith Distribution” because we are at the South Pole

- **Compatible with isotropic flux**
- **Events absorbed in Earth from Northern Hemisphere**
- **Minor excess in south compared to isotropic, but not significant**



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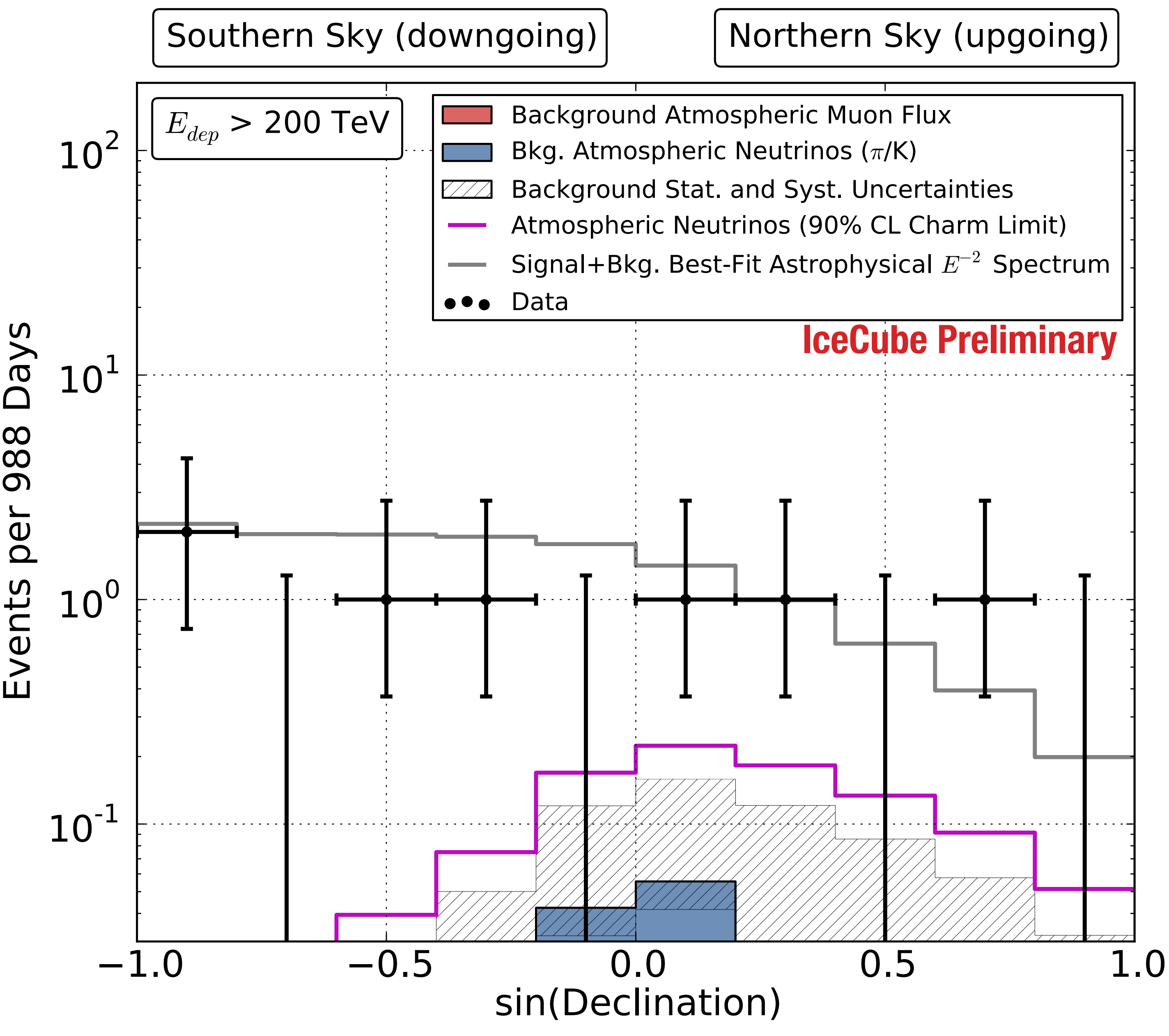
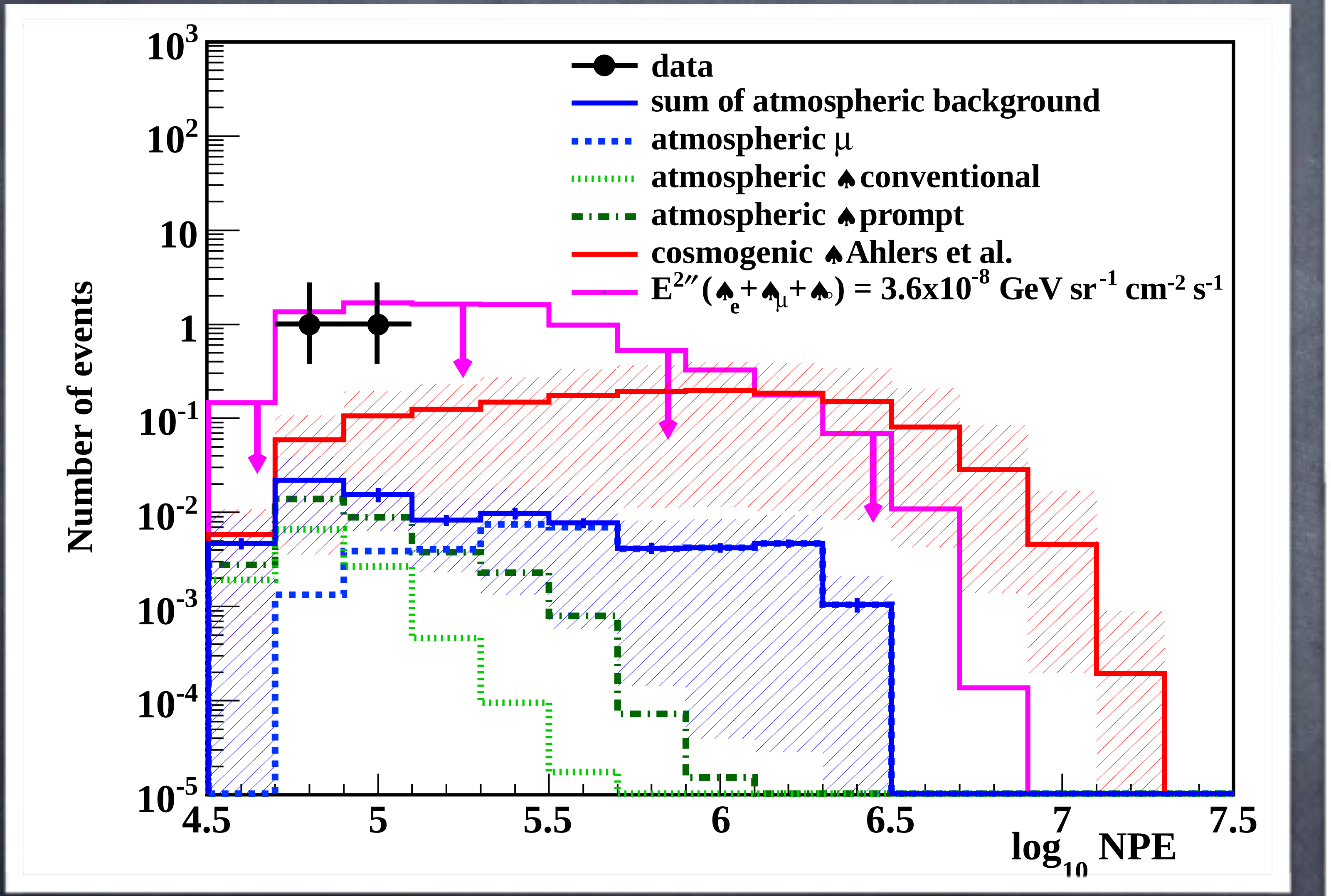
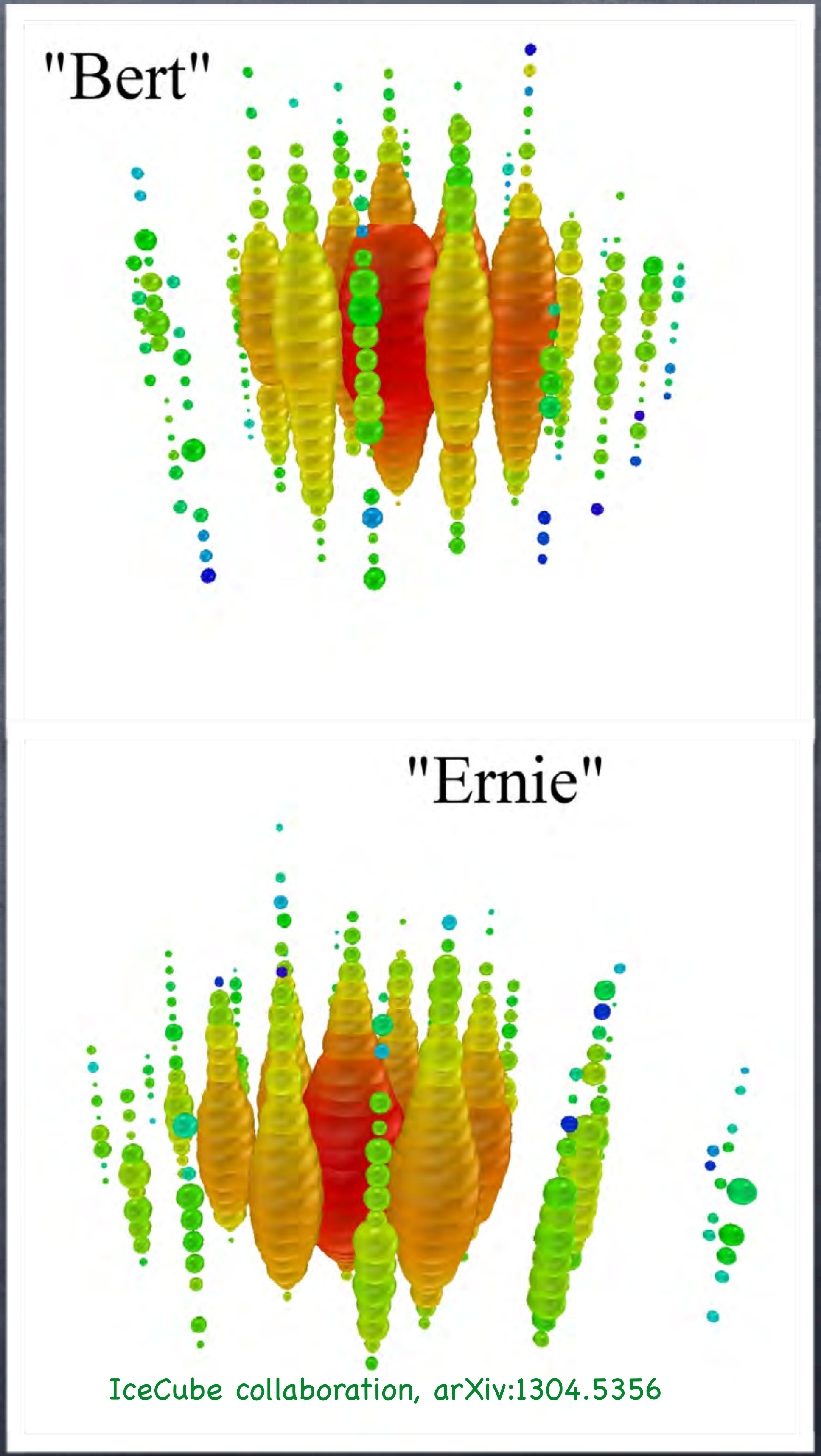


But now two PeV energy candidate neutrinos observed by IceCube



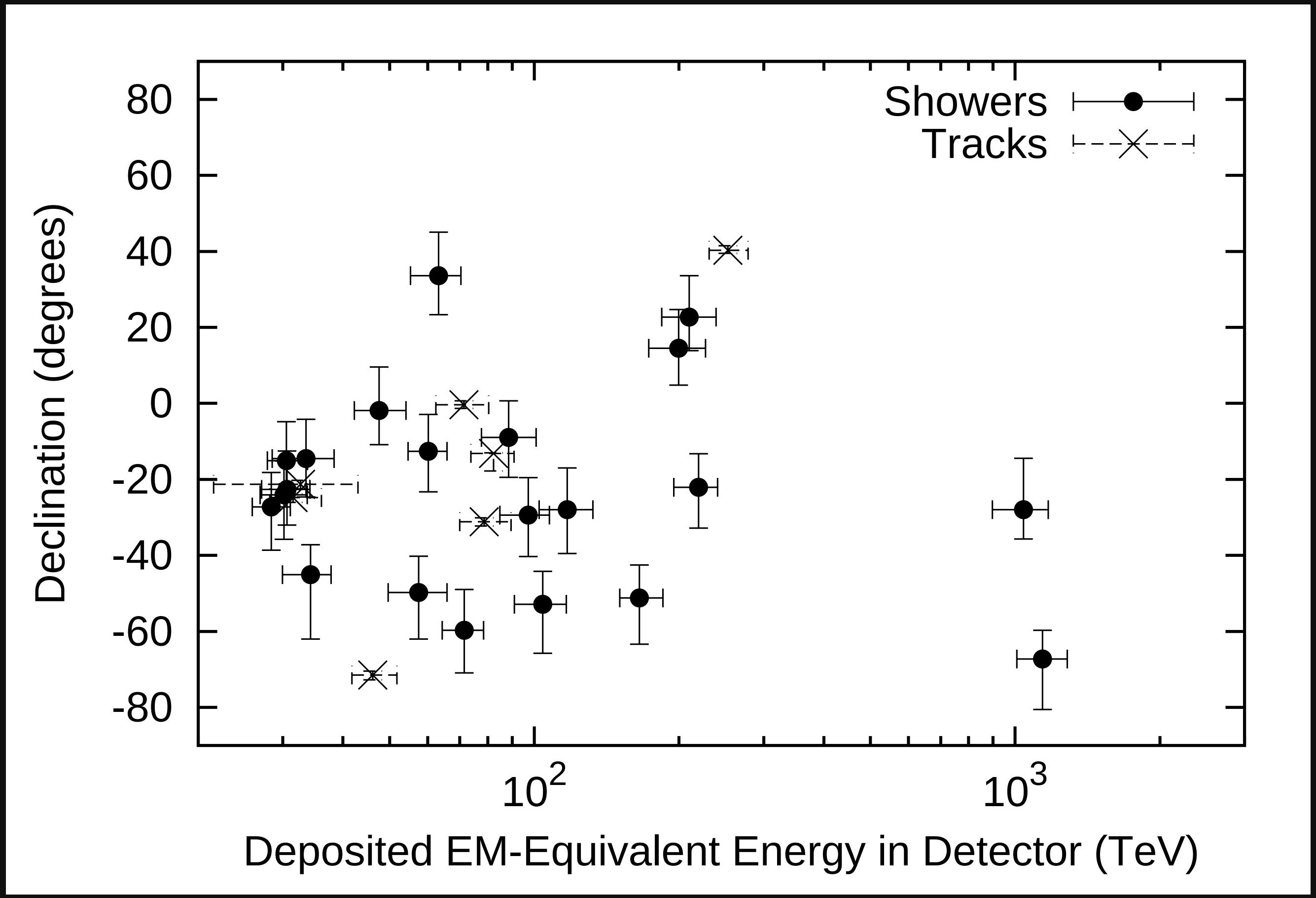


IceCube collaboration, arXiv:1304.5356

What Did We Find?

28 events in **2 years** of IceCube data
(662 days between 2010–2012)

- **28 events observed!**
  - 26 new events in addition to the two 1 PeV events!
- **Estimated background:**
  - $4.6^{+3.7}_{-1.2}$ atm. neutrinos
  - 6.0±3.4 atm. muons



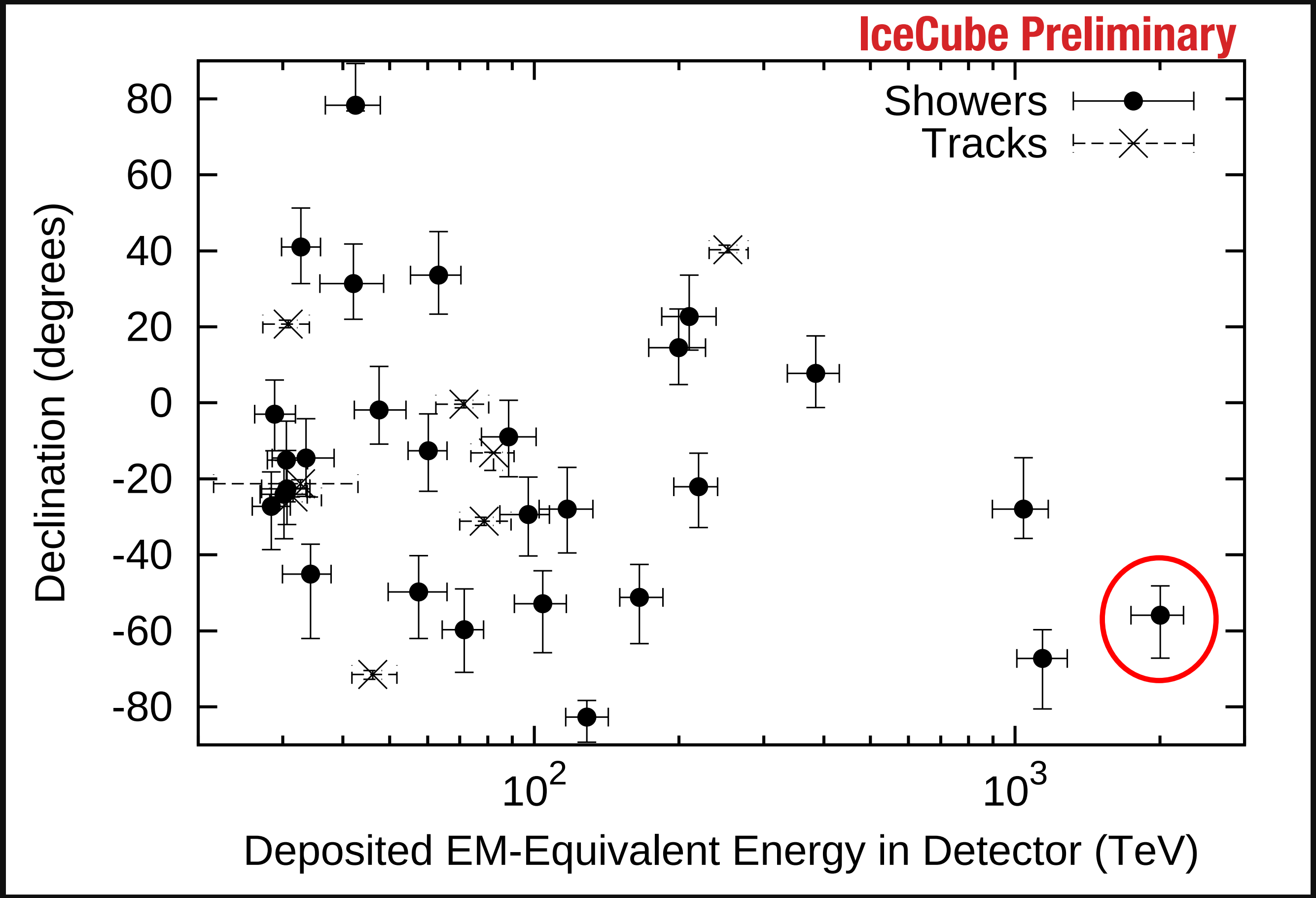
significance w.r.t. reference bkg. model:
3.3σ for 26 events
combining with 2.8σ from GZK result:
4.1σ for 26+2 events
full likelihood fit of all components:
4.1σ for 28 events

What Did We Find?

37 events in **3 years** of IceCube data
(988 days between 2010–2013)

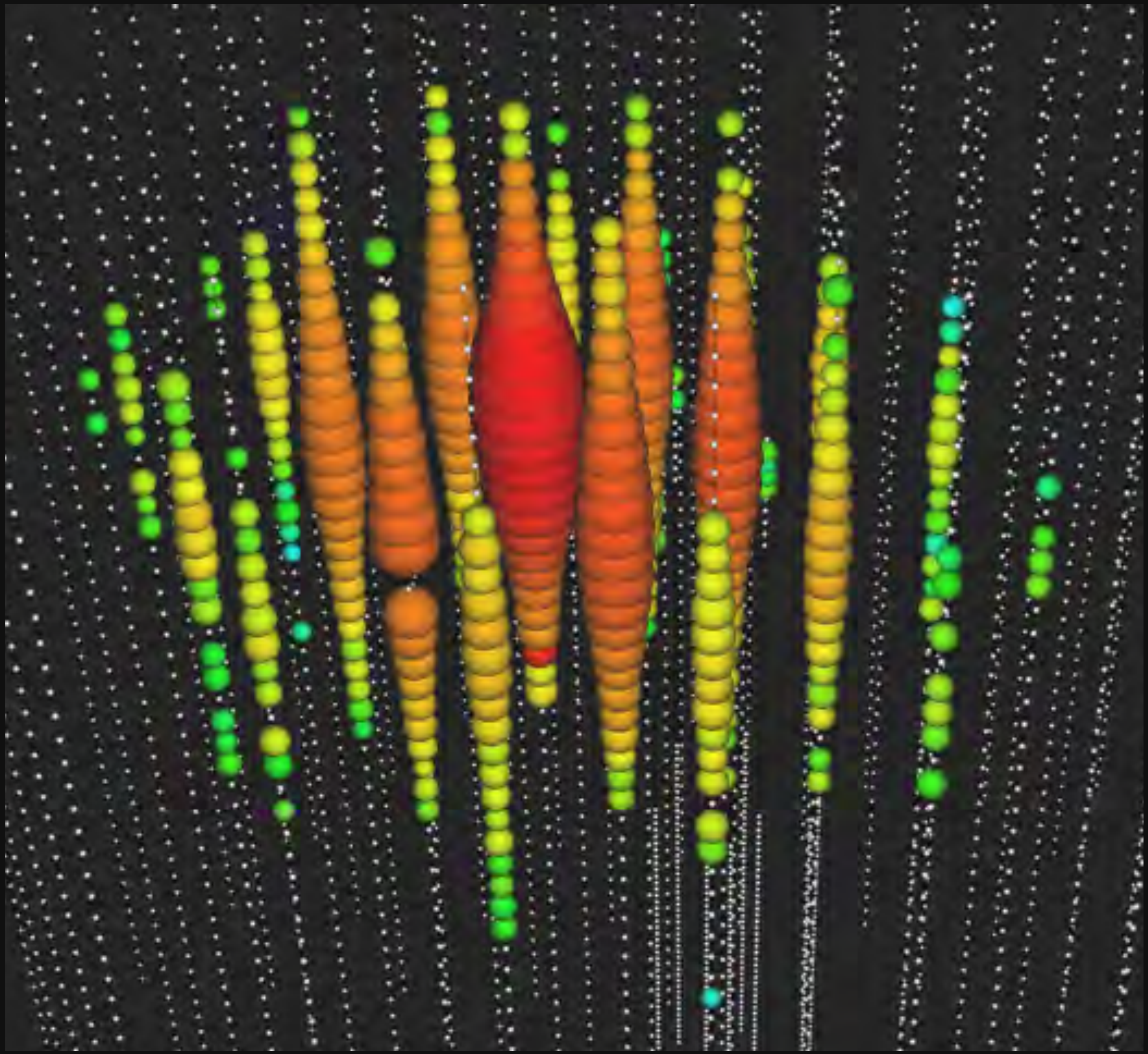
Preliminary

- **37 events observed!**
  - 35 new events in addition to the two 1 PeV events!
- **Estimated background:**
  - $6.6^{+5.9}_{-1.6}$ atm. neutrinos
  - 8.4 ± 4.2 atm. muons
- **One of them is an obvious (but expected) background**
  - coincident muons from two CR air showers



combining with 2.8σ from GZK result:
4.8σ for 35+2 events
full likelihood fit of all components:
5.7σ for 36(+1) events

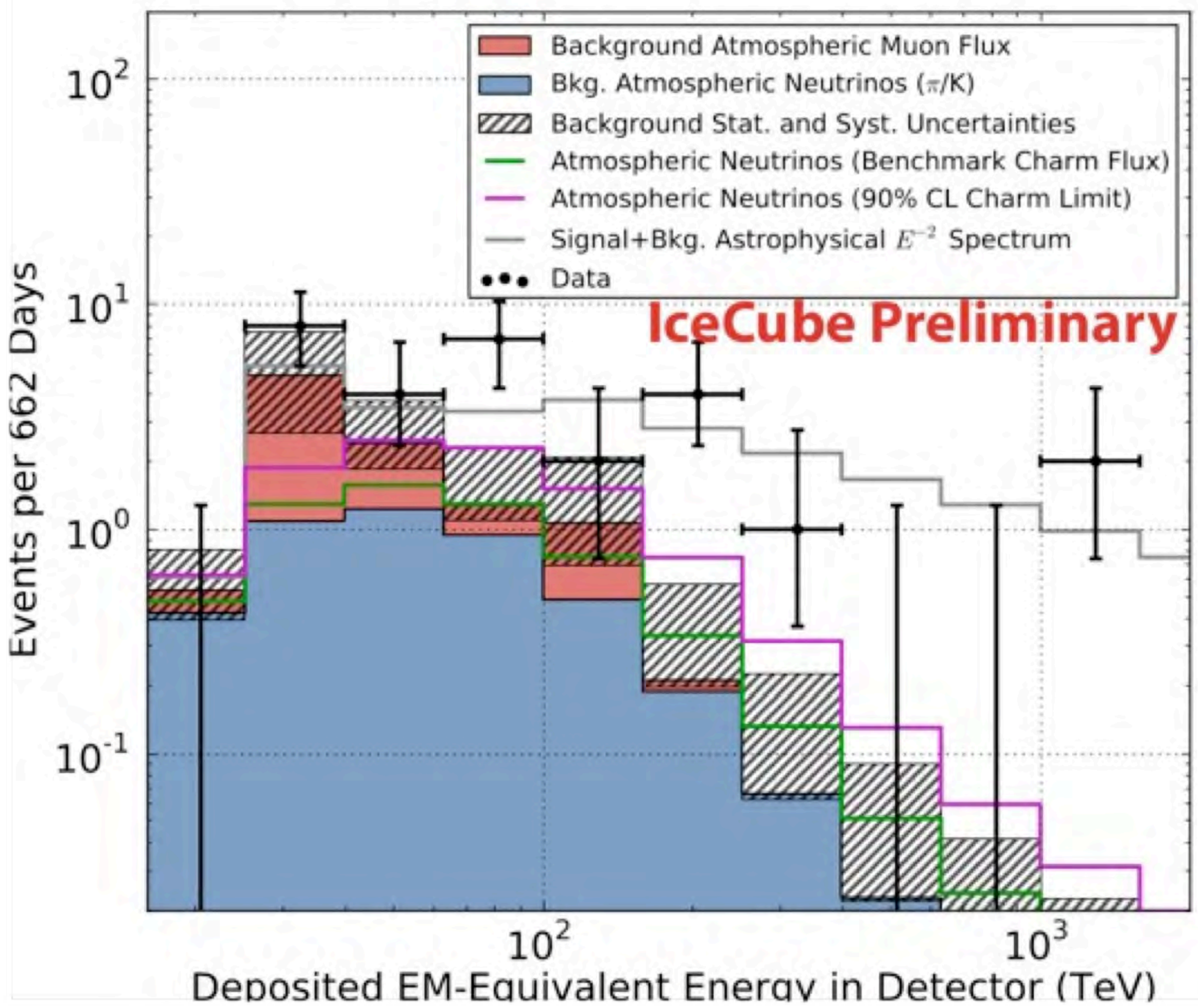
Thank you!

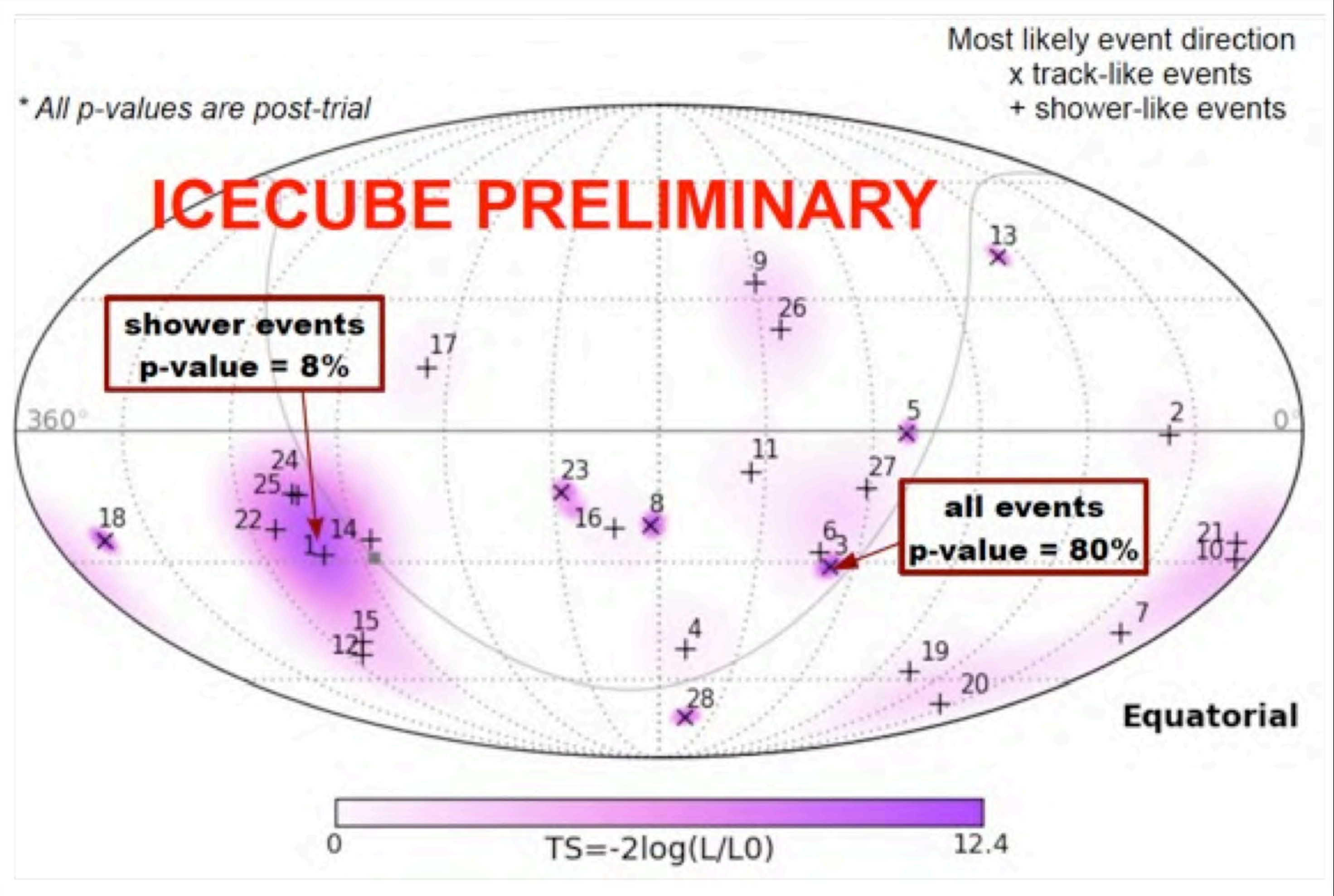


2 PeV event - “Big Bird”

and even more events at few 100 TeV:

IceCube ICRC 2013

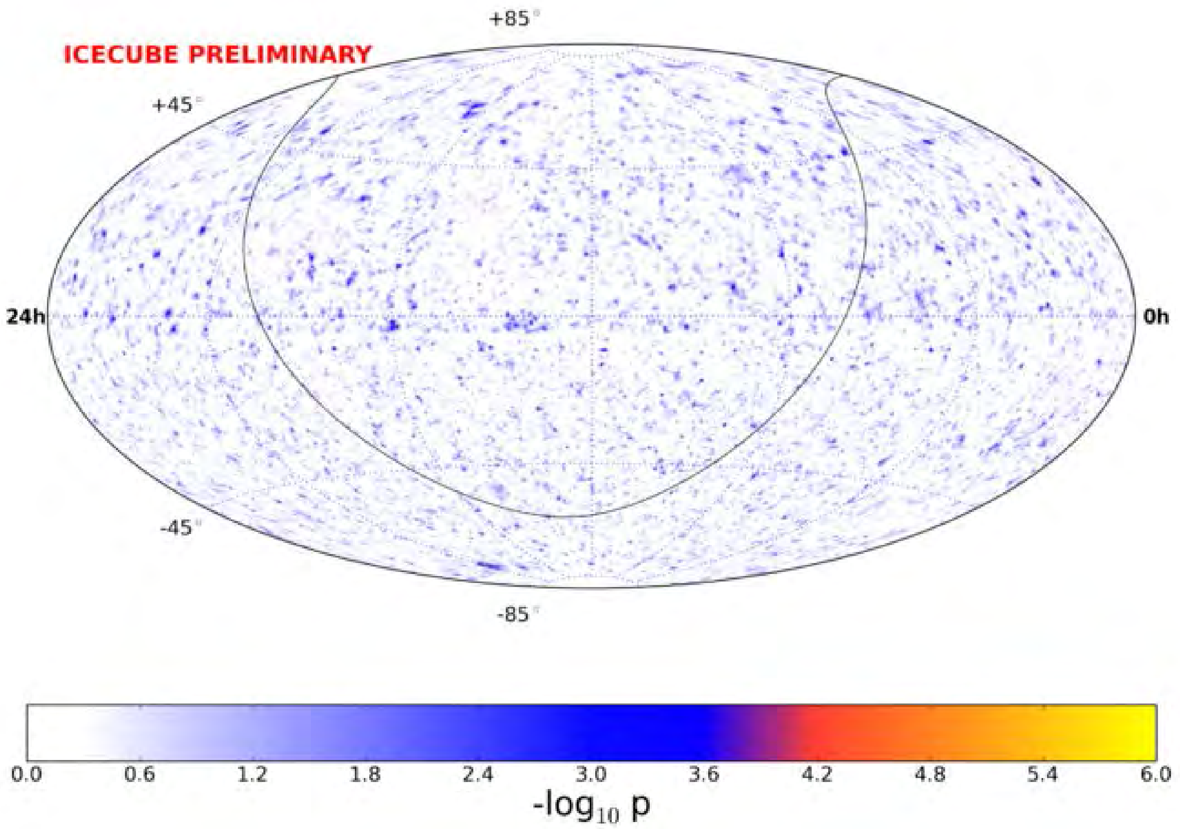




4 year neutrino sky map

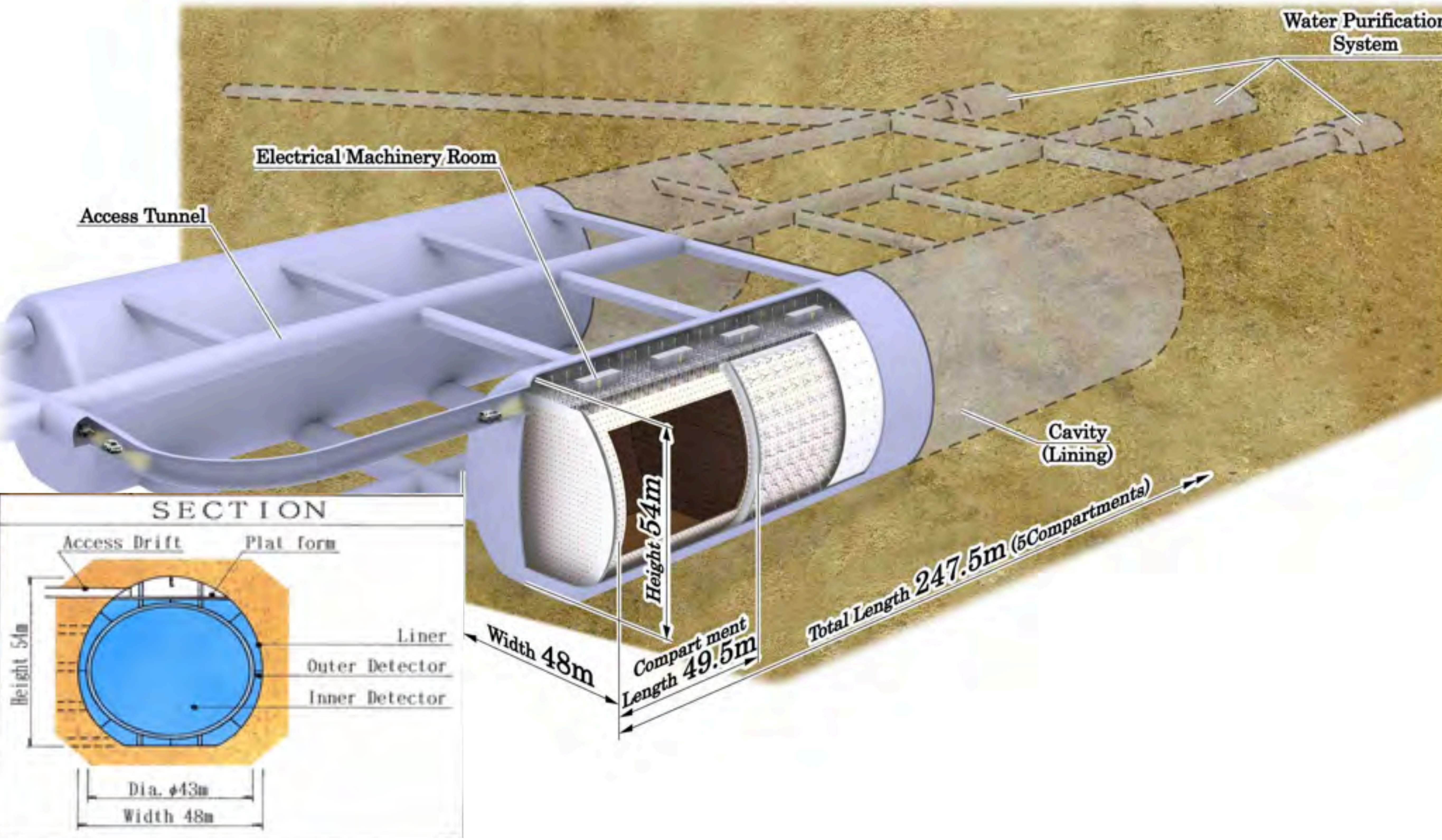
- 1371 live days, with 390,000 events
  - ◆ No significant excesses seen
  - ◆ Sensitivity depends on declination
    - ☞ Flux limits $E^2\,\phi < 10^{-12}$ TeV/cm^2/s near the horizon

Paper 0550

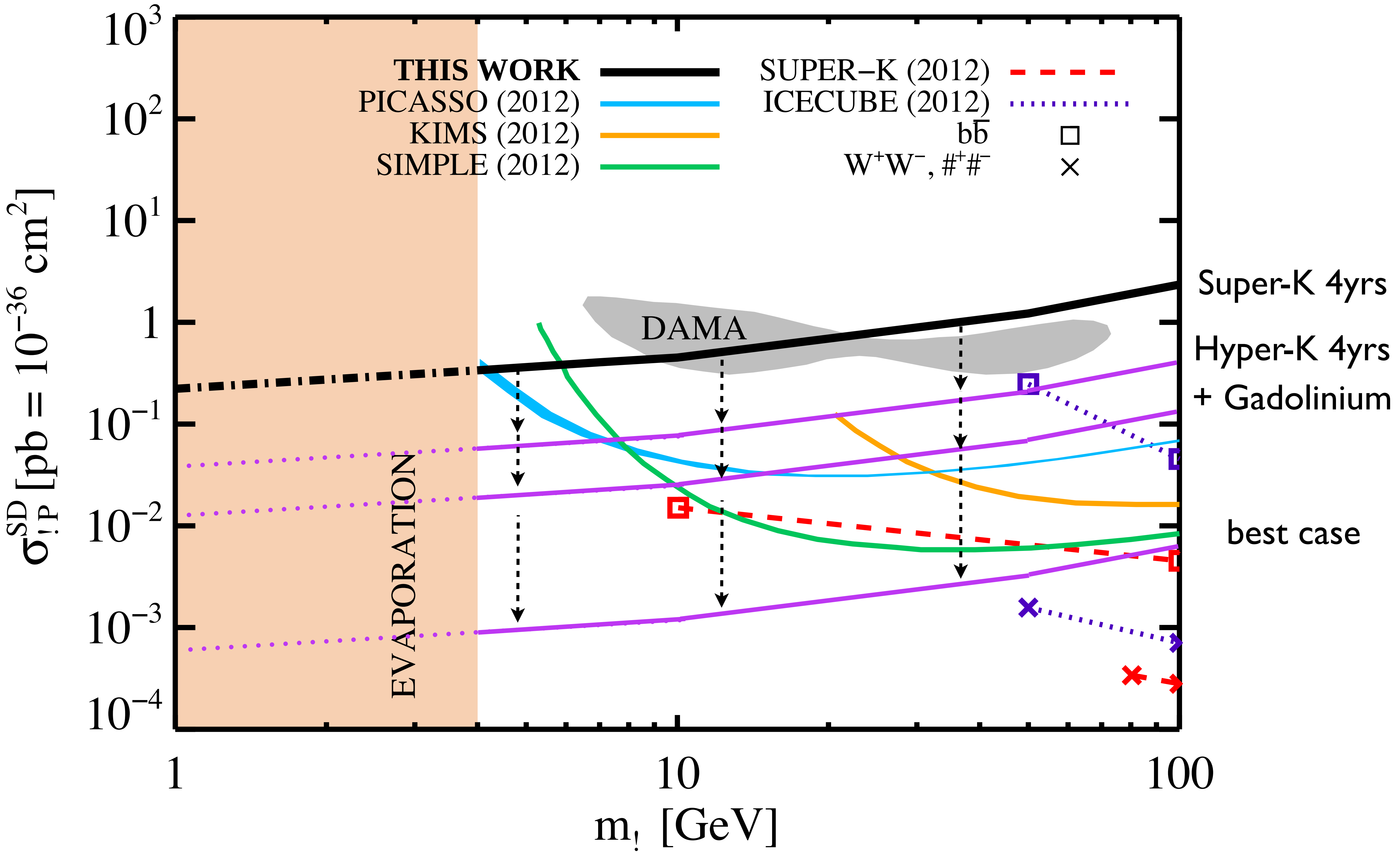


Hyper-K

Hyper-K LOI arXiv:1109.3262



Hyper-K Sensitivity 4yrs



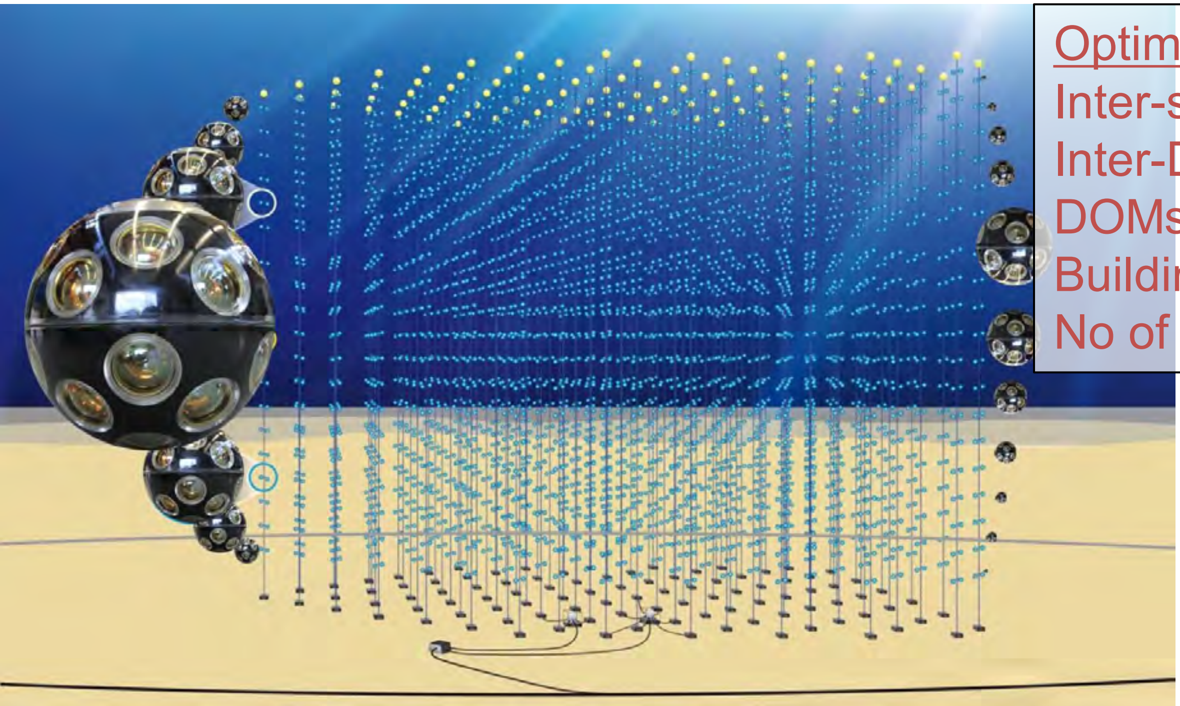
Interesting signatures for future neutrino detectors (Hyper-K, MICA (see Talk by E. Resconi), LBNE, ...), other nuclear final states could provide additional sensitivity

NU-IN01 **P. Coyle (891)**

NU-TH01 **A. Trovato(165)**

KM3NeT

Multi-km^3 neutrino telescope in the Mediterranean Sea



Optimal detector parameter

Inter-string spacing: ~90m
Inter-DOM spacing: ~36m
DOMs/string: 18
Building block: ~115 strings
No of building blocks: 6

Deploy method tested.

Discovery of RXJ1713.7-3946 (Vela X) after about 5 (3.3) observation years.

Phase 1 funding secured.

Decision taken for distributed infrastructure:
- KM3NeT-France (Toulon) ~2500m
- KM3NeT-Italy (Capo Passero) ~3400m
- KMNeT-Greece (Pylos) ~4500m