Status of IceCube-DeepCore: Sensitivity study for the Southern Hemisphere.

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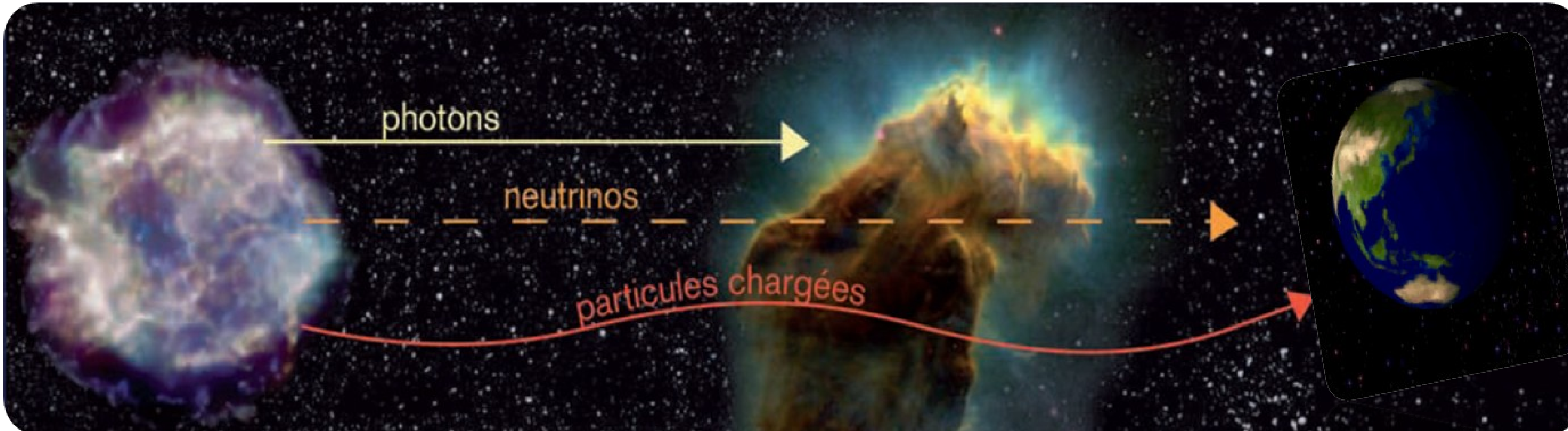
CONTENT

- Neutrino Astronomy: a short introduction
- The IceCube neutrino telescope
- IceCube: preliminary results
- Beyond IceCube: the IceCube-DeepCore detector
- Point source analysis for the Southern Hemisphere

Neutrino Astronomy



Advantages of neutrinos:

Electrically neutral ➔ not bent by the ambient magnetic fields (unlike cosmic-rays)
➔ their direction point back to their source

Weakly interacting ➔ No absorption: observation at cosmological distances (unlike photons)

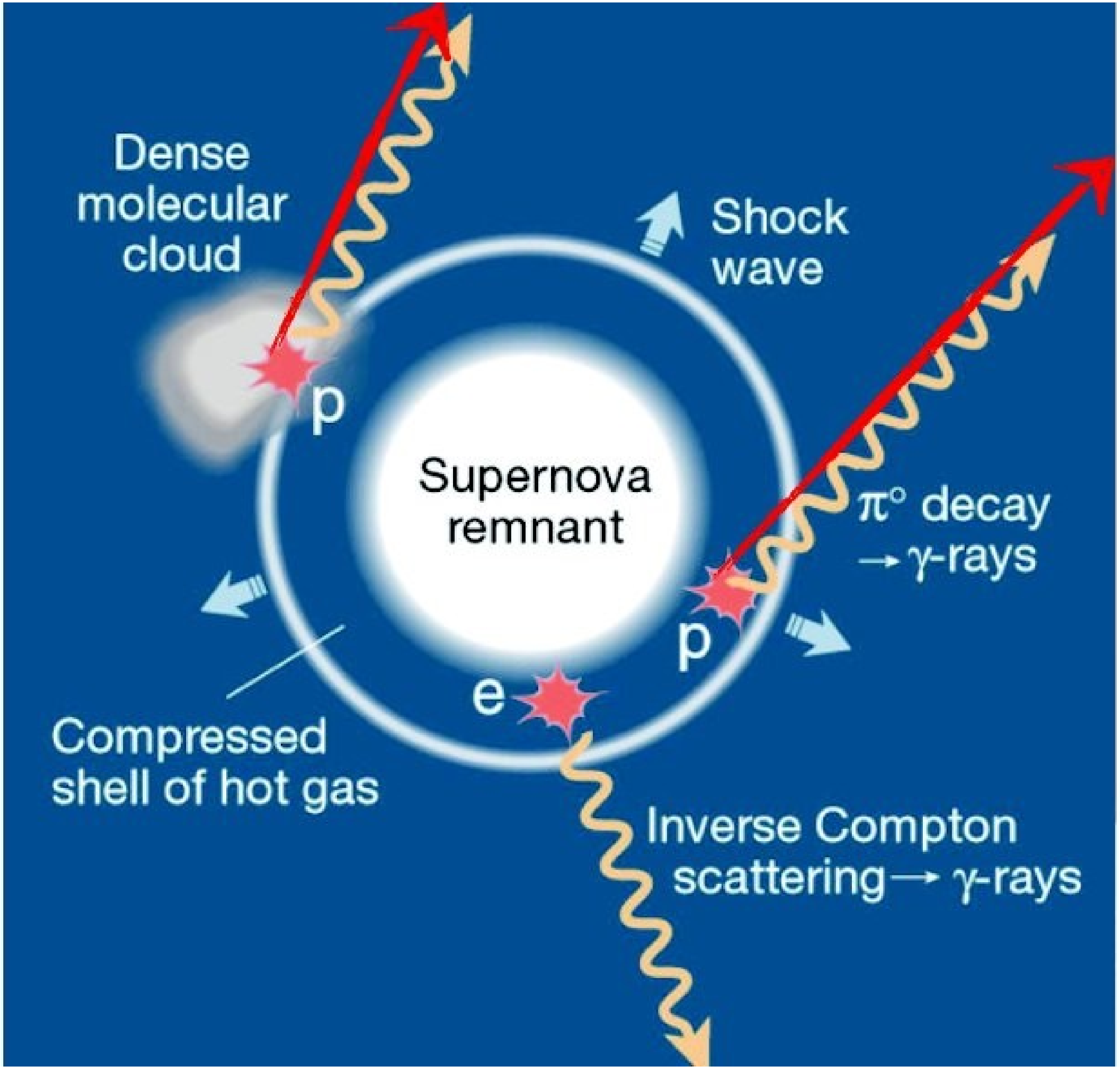
➔ escape from the dense areas of the Universe (core of stars, ect.)

➔ Neutrinos are an ideal probe to observe distant astrophysical objects and provide information on the dynamics of the most energetic phenomena of the Universe.

➔ Neutrino might shed light on the origin of very high energy cosmic rays

Extragalactic and Galactic cosmic-rays accelerators

modified from F.Aharonian, Nature 416, 797-798 (25 April 2002)



Π± → υ

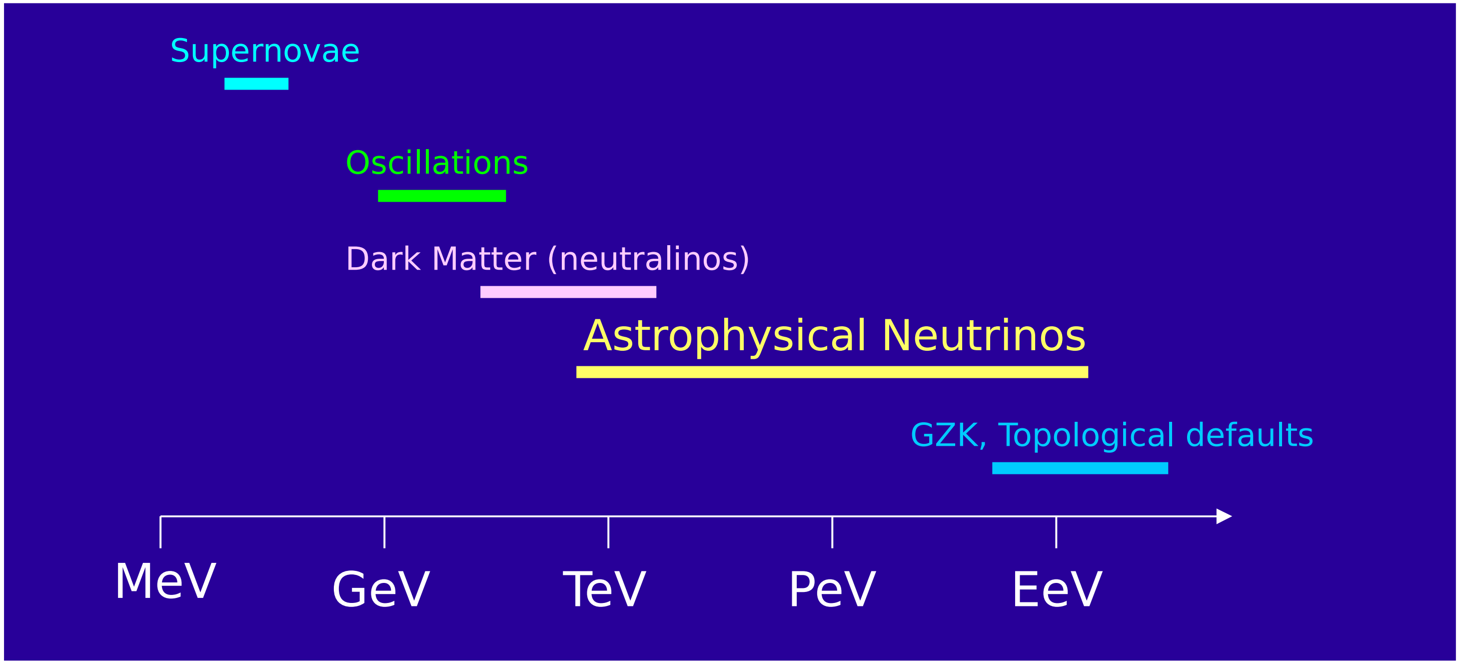
υ not produced in leptonic interactions.

Neutrino Astronomy

- Extragalactic/Galactic Cosmic Rays accelerators (AGN, GRBs, microquasars, SNRs)
- Indirect dark matter searches
- Beyond the Standard Model (Lorentz symmetry violation, monopoles ect.)

Specific to IceCube:

- Supernovae explosions
- Primary Cosmic Rays around the Knee (Cosmic Rays anisotropy/Icetop)

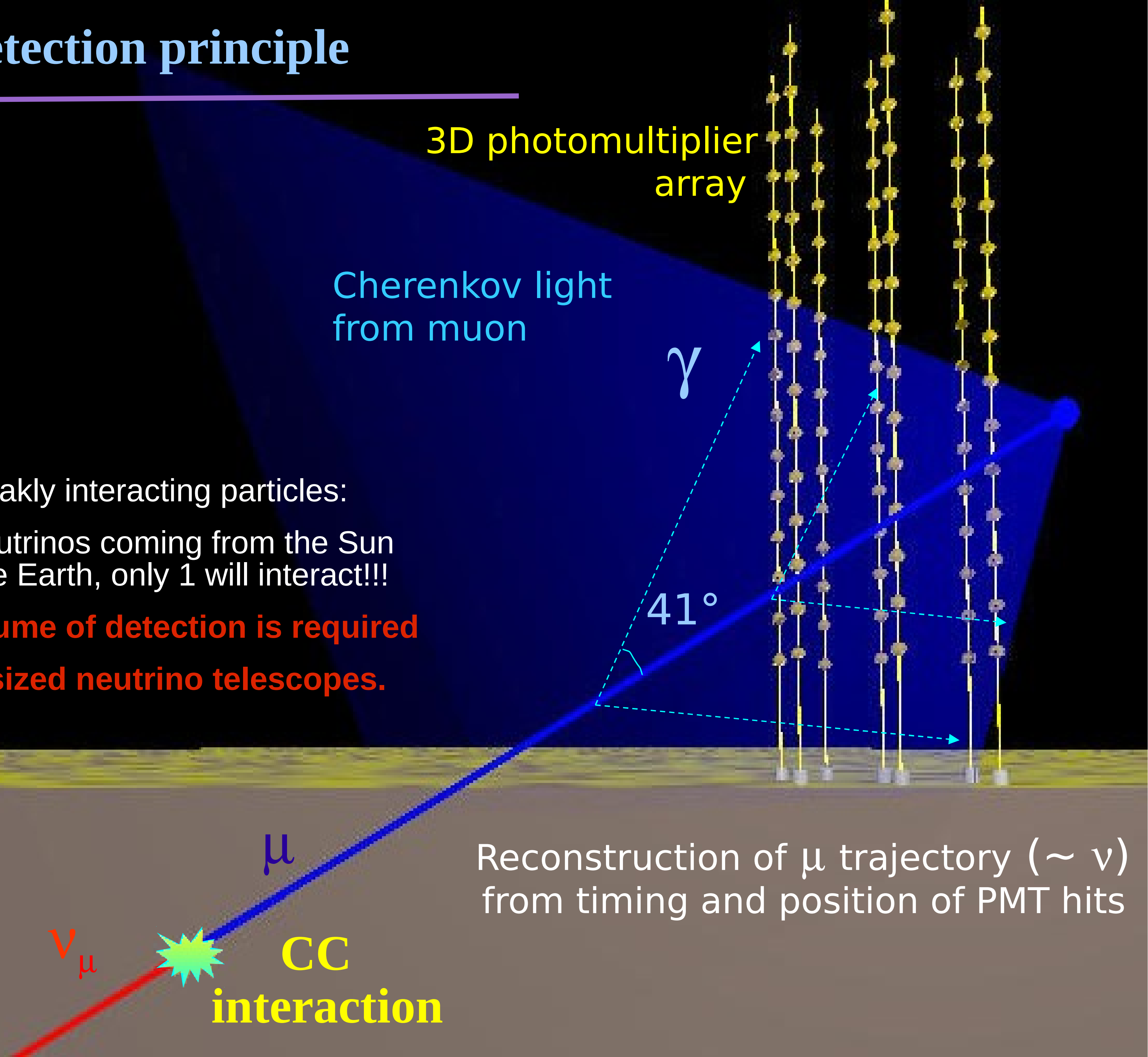


Neutrino detection principle

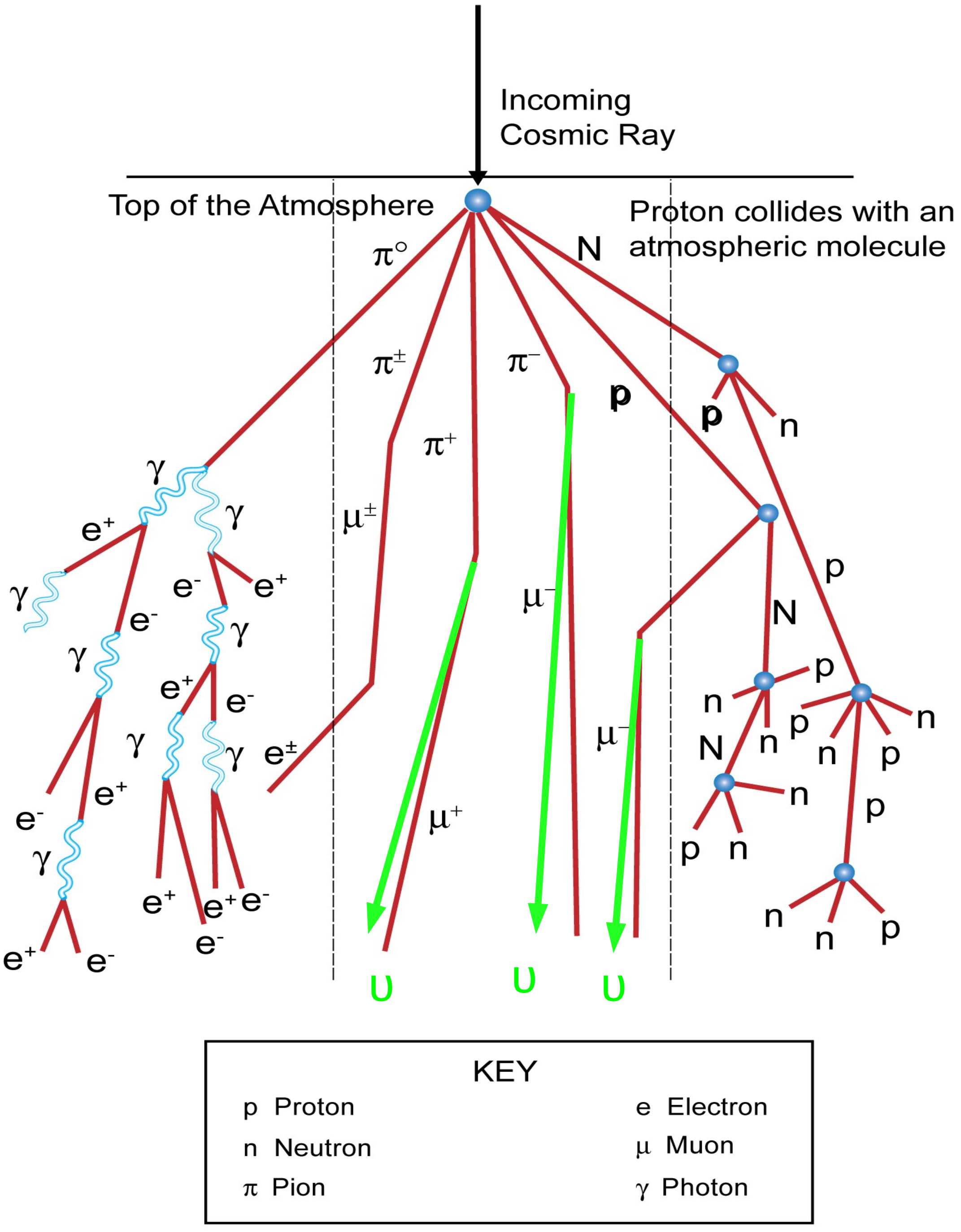
Neutrino are weakly interacting particles:

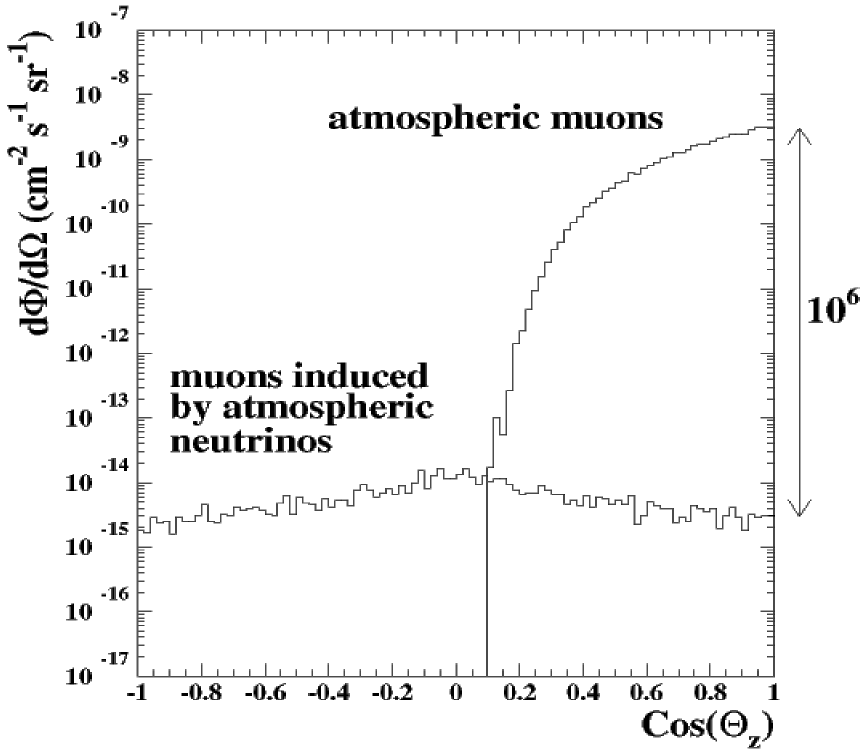
On 10 billion neutrinos coming from the Sun and crossing the Earth, only 1 will interact!!!

- ➔ **A large volume of detection is required**
- ➔ **Kilometer sized neutrino telescopes.**



The Atmospheric background





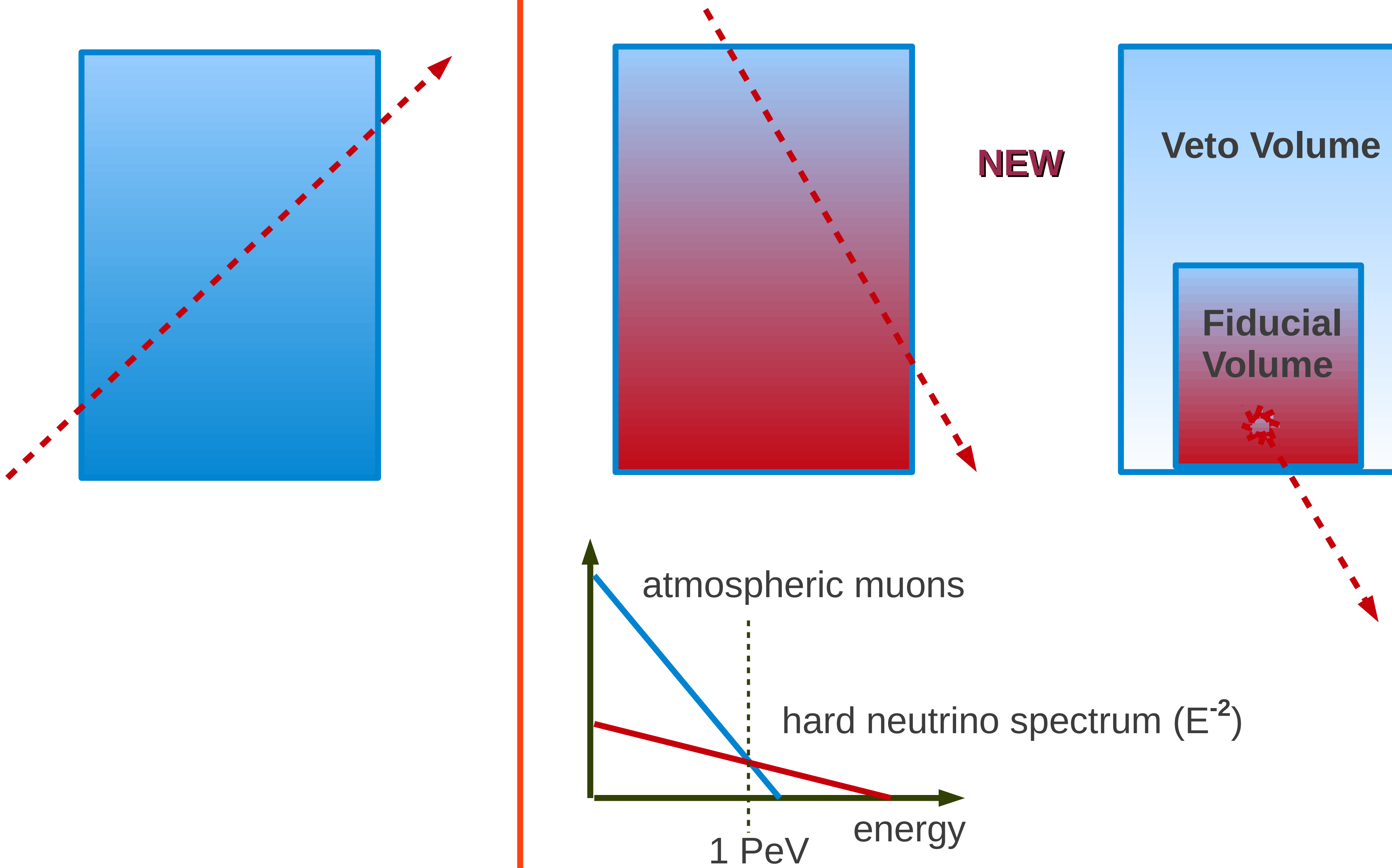
The field of view of a neutrino telescope

Upward through-going

Very high energy downward

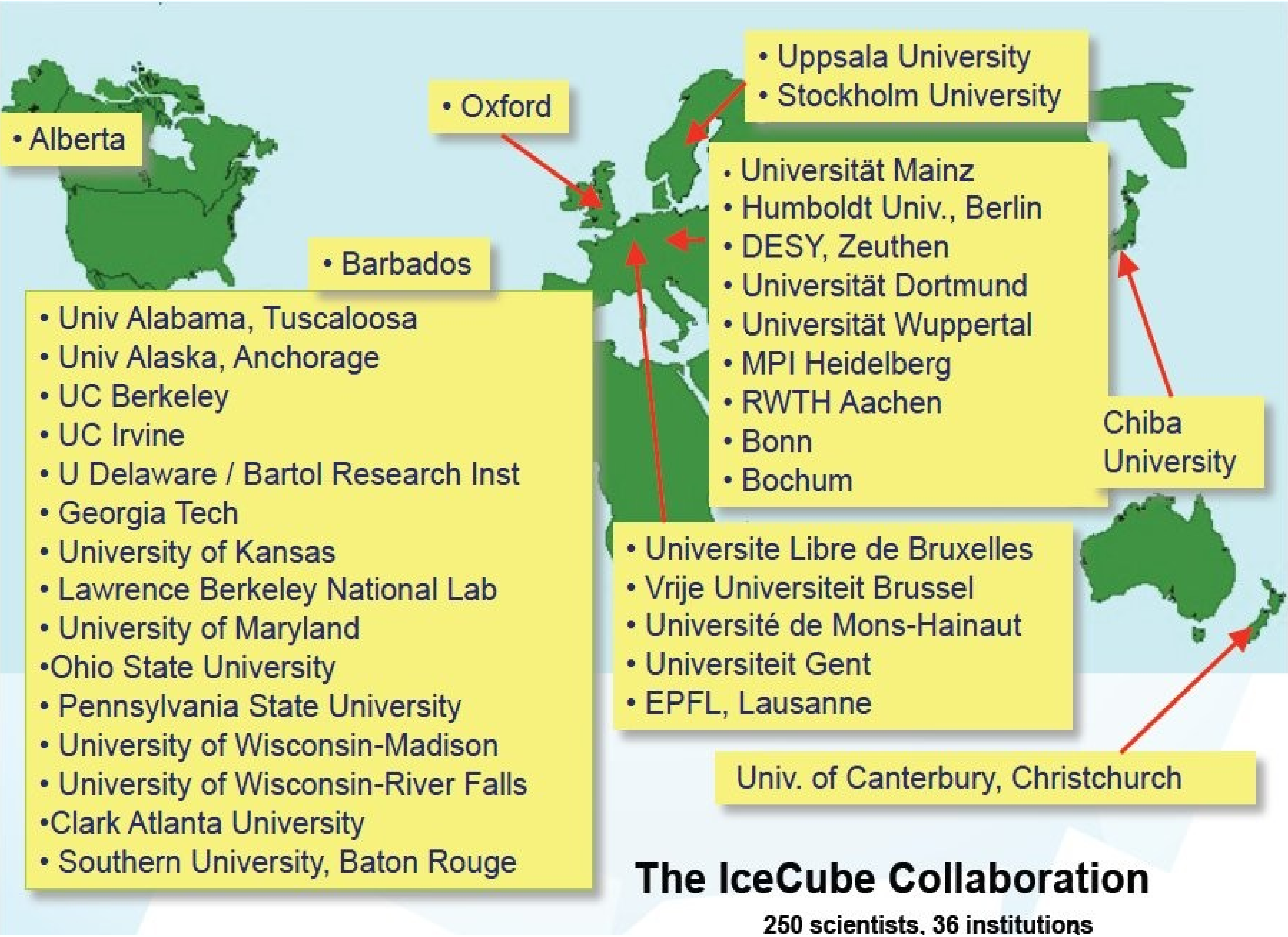
Fully/Semi-contained

Cubic Kilometer sized telescopes only



IceCube

- The Collaboration
- The neutrino telescope
- Preliminary results



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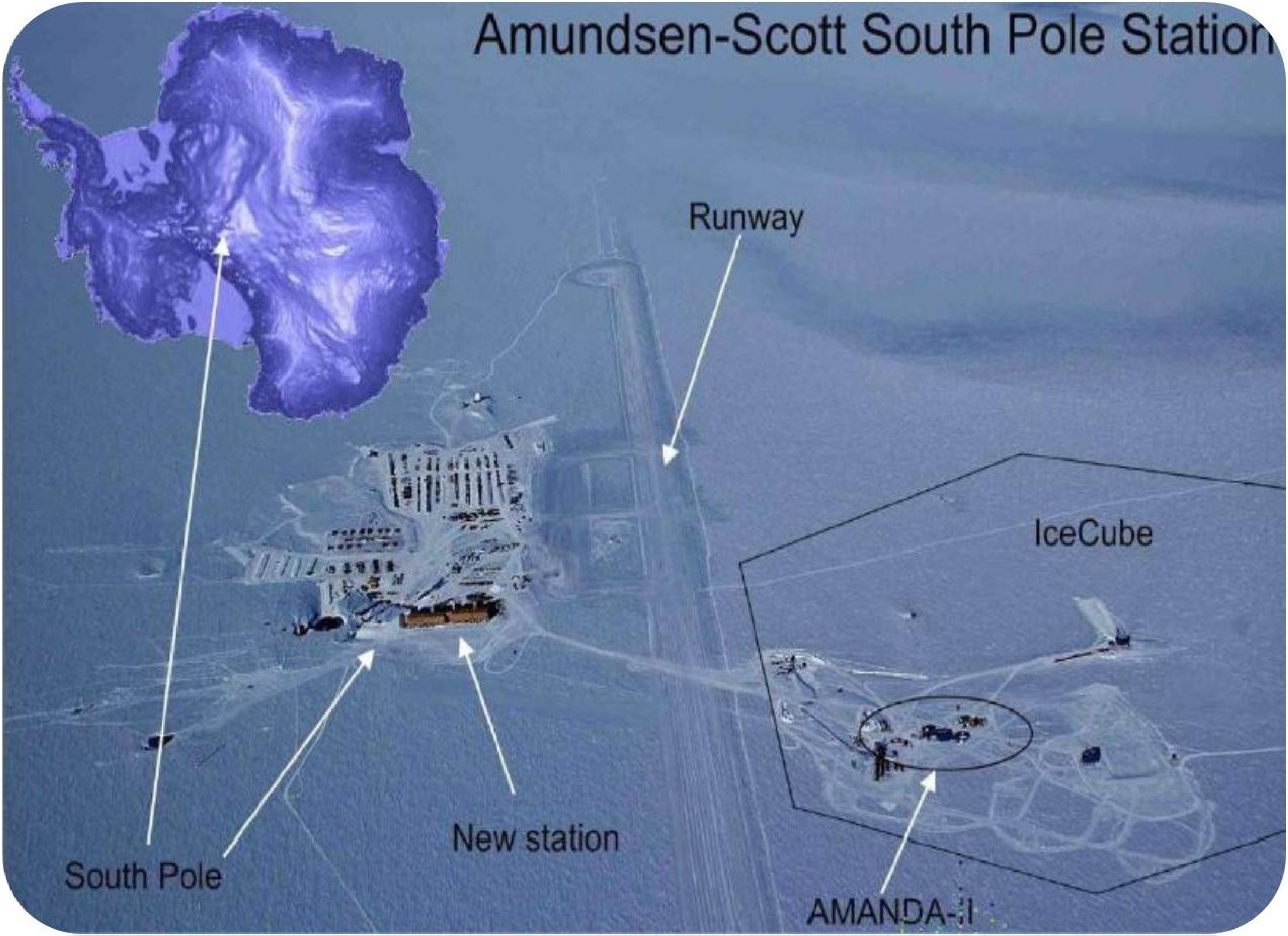
The IceCube Collaboration
250 scientists, 36 institutions


Amundsen-Scott South Pole Station
Runway
IceCube
New station
South Pole
AMANDA-II

IceCube

- 5168 DOMs/86 strings
- 60 DOMs/string
- Spacing:

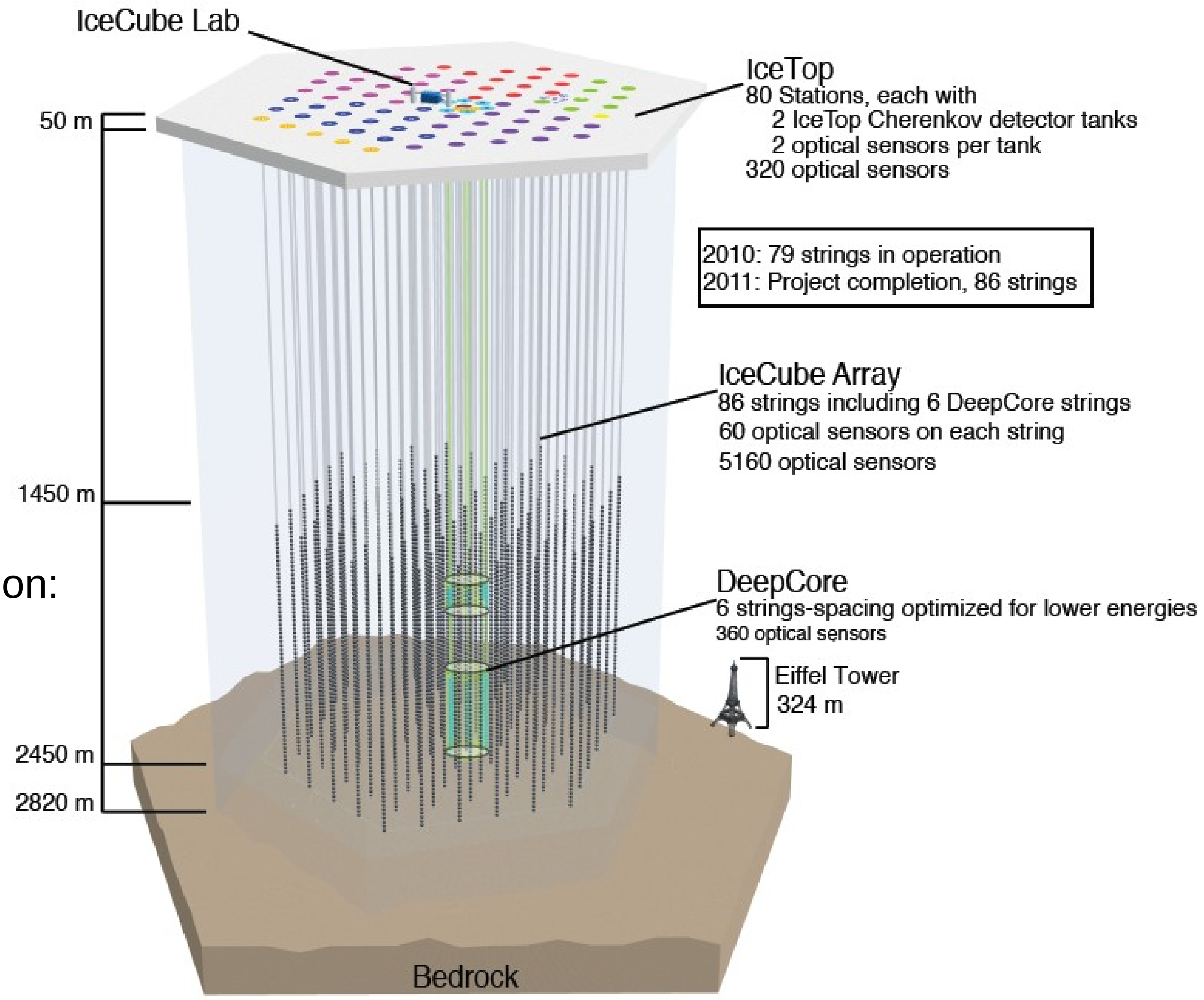
~ 125m between lines

~ 17m between DOMs

- Angular resolution: ~0.4-1°

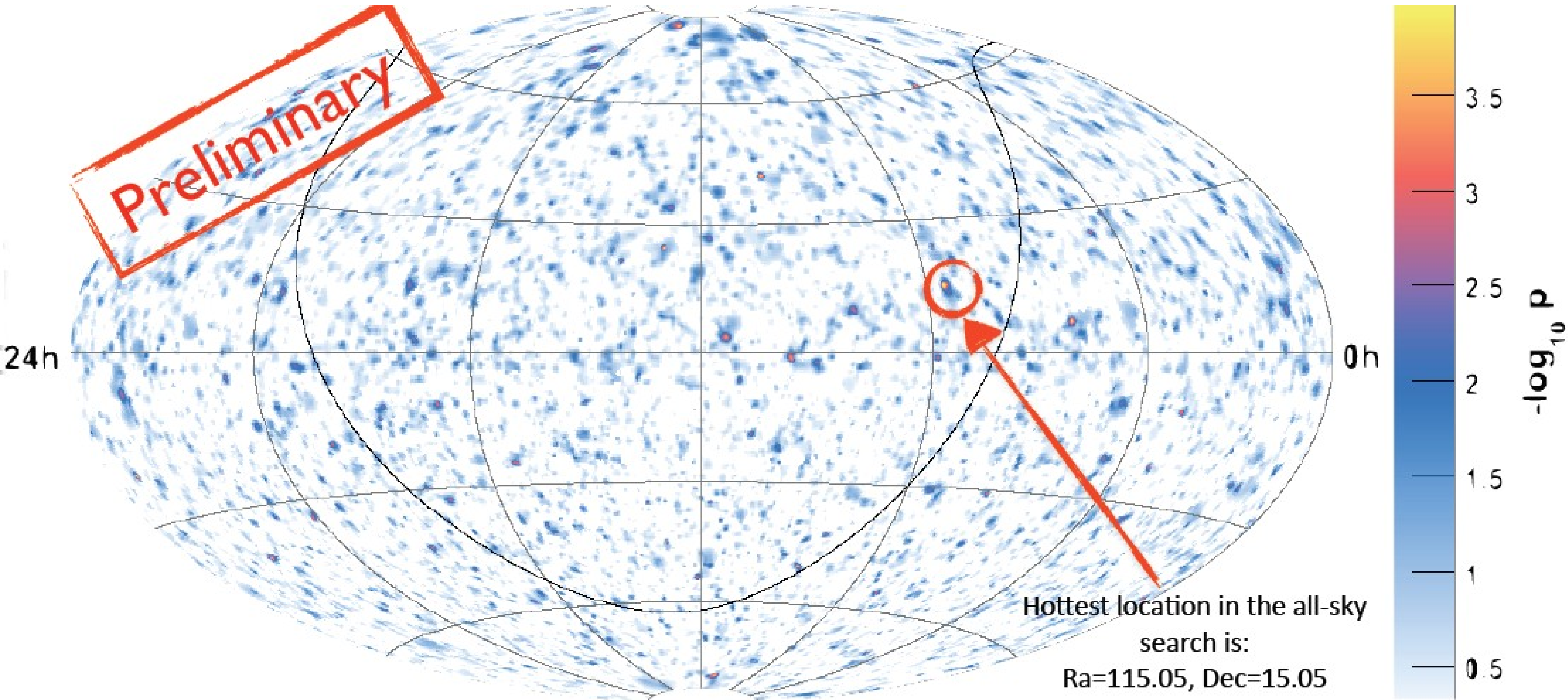
IceCube taken during construction:

2006-7 data set: IC9
2007-8 data set: IC22
2008-9 data set: IC40
2009-10 data set: IC59
Current configuration: IC79



Point Source Search IC40

Northern Hemisphere
Background: Atmospheric Neutrinos



Southern Hemisphere
Background: Atmospheric Muons

Pre-trials significance

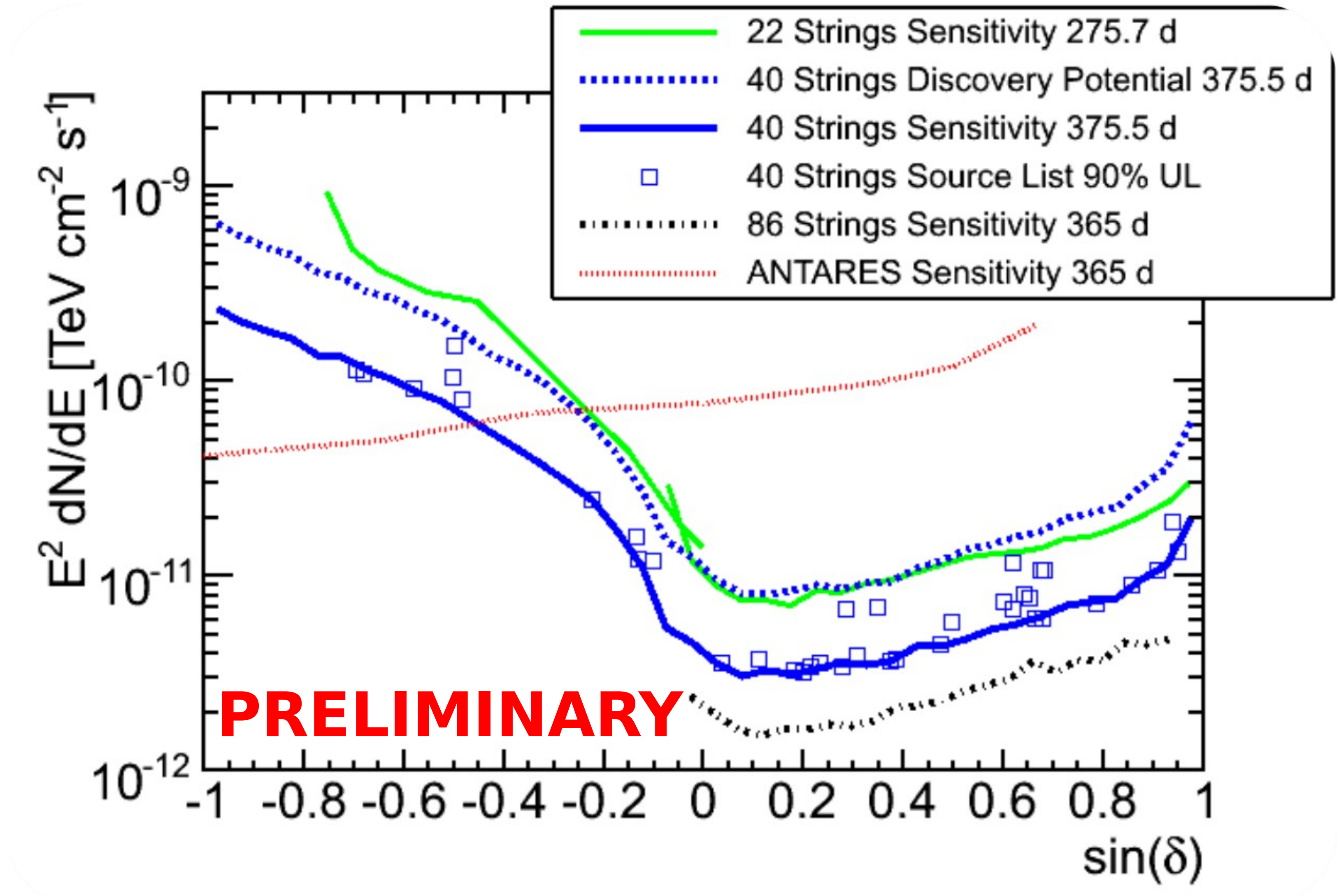
All-sky p-value = 18%
Not significant, no evidence of a neutrino source

Livetime = 375.5 days

Events = 36900
(14121 up-going,
22779 down-going)

Source: J.Dumm et al., 31st ICRC Lodz 2009

Sensitivity at the 90% C.L. for IC40



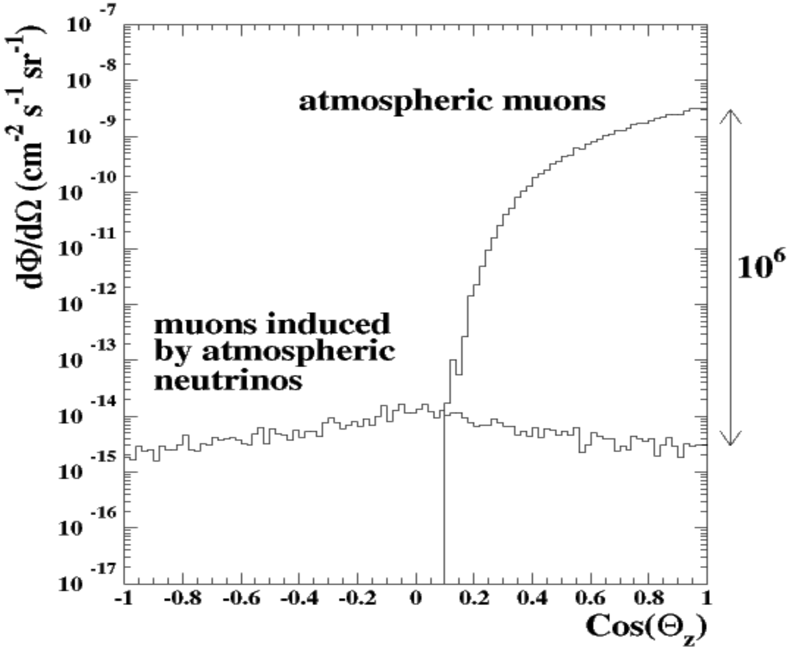
Northern Hemisphere: $E^2 \cdot \Psi(E) \sim 2-200 \cdot 10^{-12} TeV \cdot cm^{-2} \cdot s^{-1} [TeV - PeV]$

Southern Hemisphere: $E^2 \cdot \Psi(E) \sim 3-700 \cdot 10^{-12} TeV \cdot cm^{-2} \cdot s^{-1} [E > PeV]$

IceCube-DeepCore

- The DeepCore detector
- The Atmospheric muon veto
- The Atmospheric neutrino veto
- Application to the Southern Hemisphere

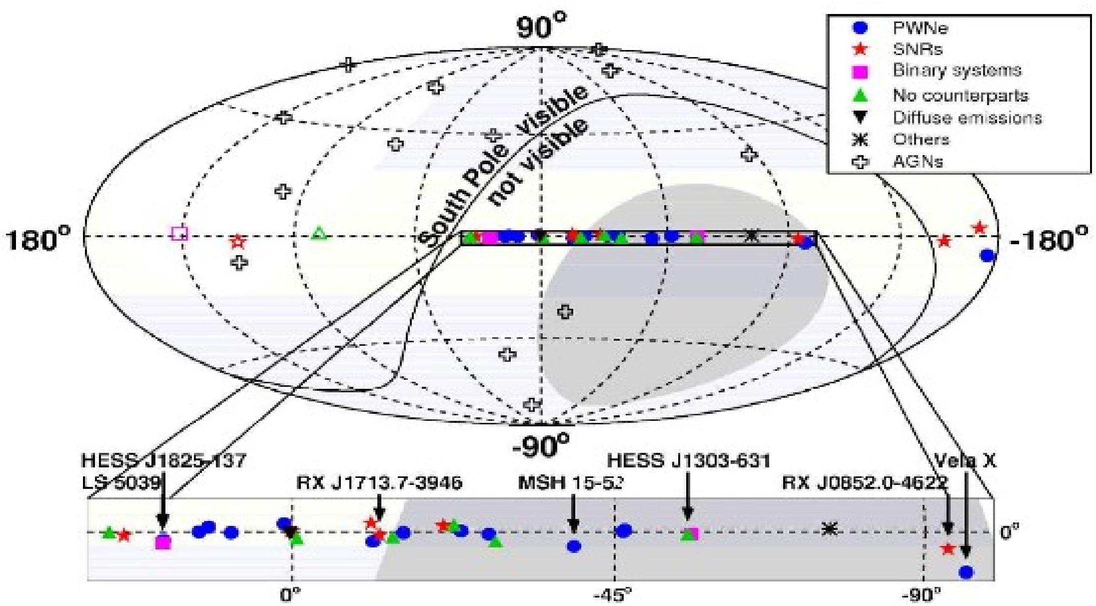
Accessing the Southern Hemisphere below 1 PeV



IceCube is at the **South Pole.**

Field of view **(E_ν < 1 PeV):**

Northern Hemisphere.



Southern Hemisphere:

At least **5 SNRs** have been detected

\+

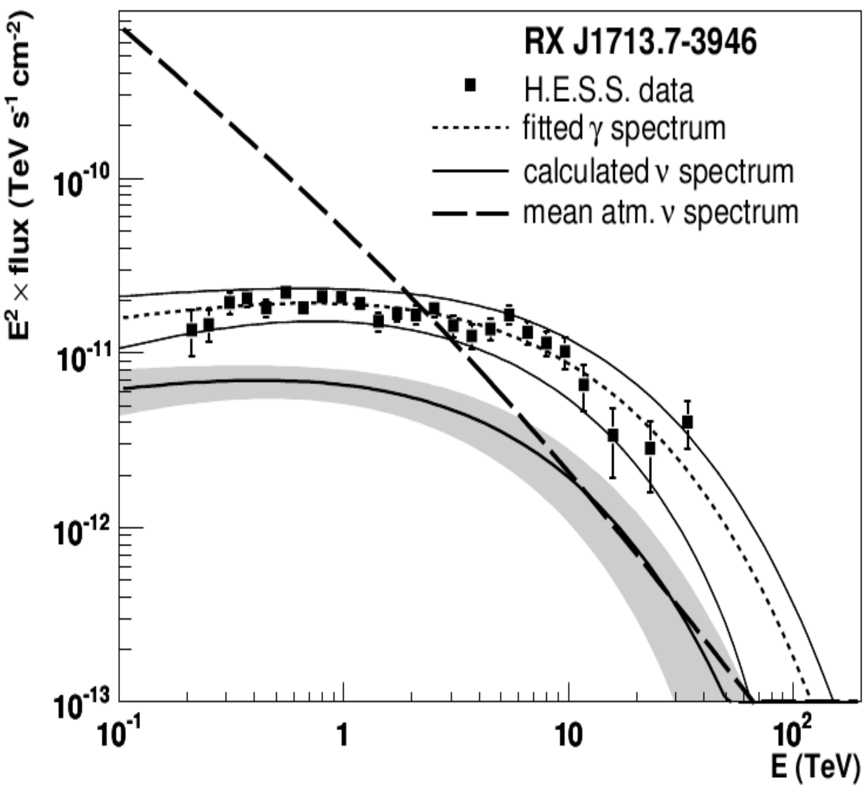
Galactic Center

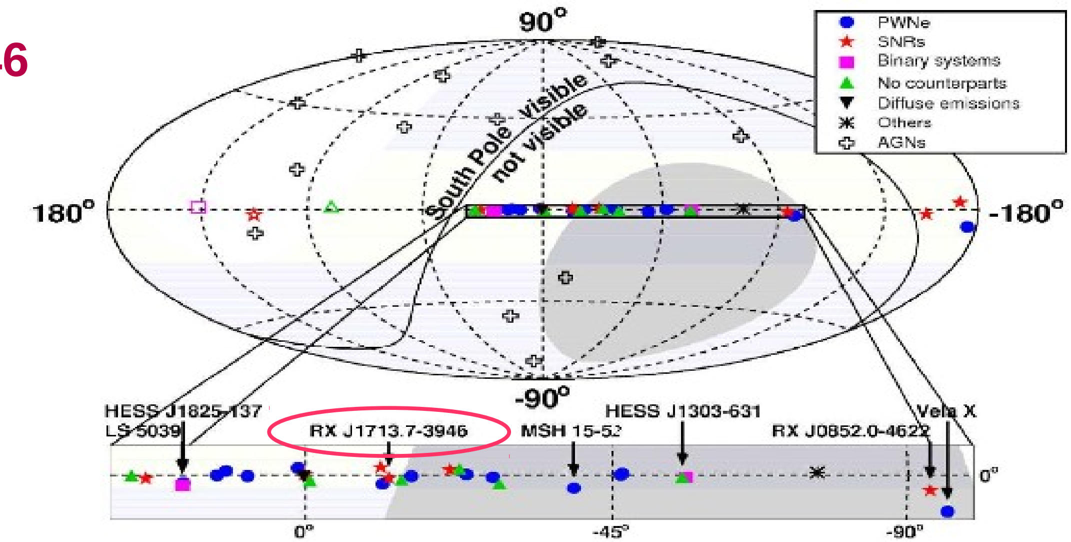
\+

Many **sources to be identified**

The link to Gamma-Ray Astronomy

Benchmark source: SNR RXJ 1713.7-3946
Right Ascension: 17:13:00 h
Declination: -39:45:00 deg
Very **young** and the **brightest** SNR of the Southern Hemisphere

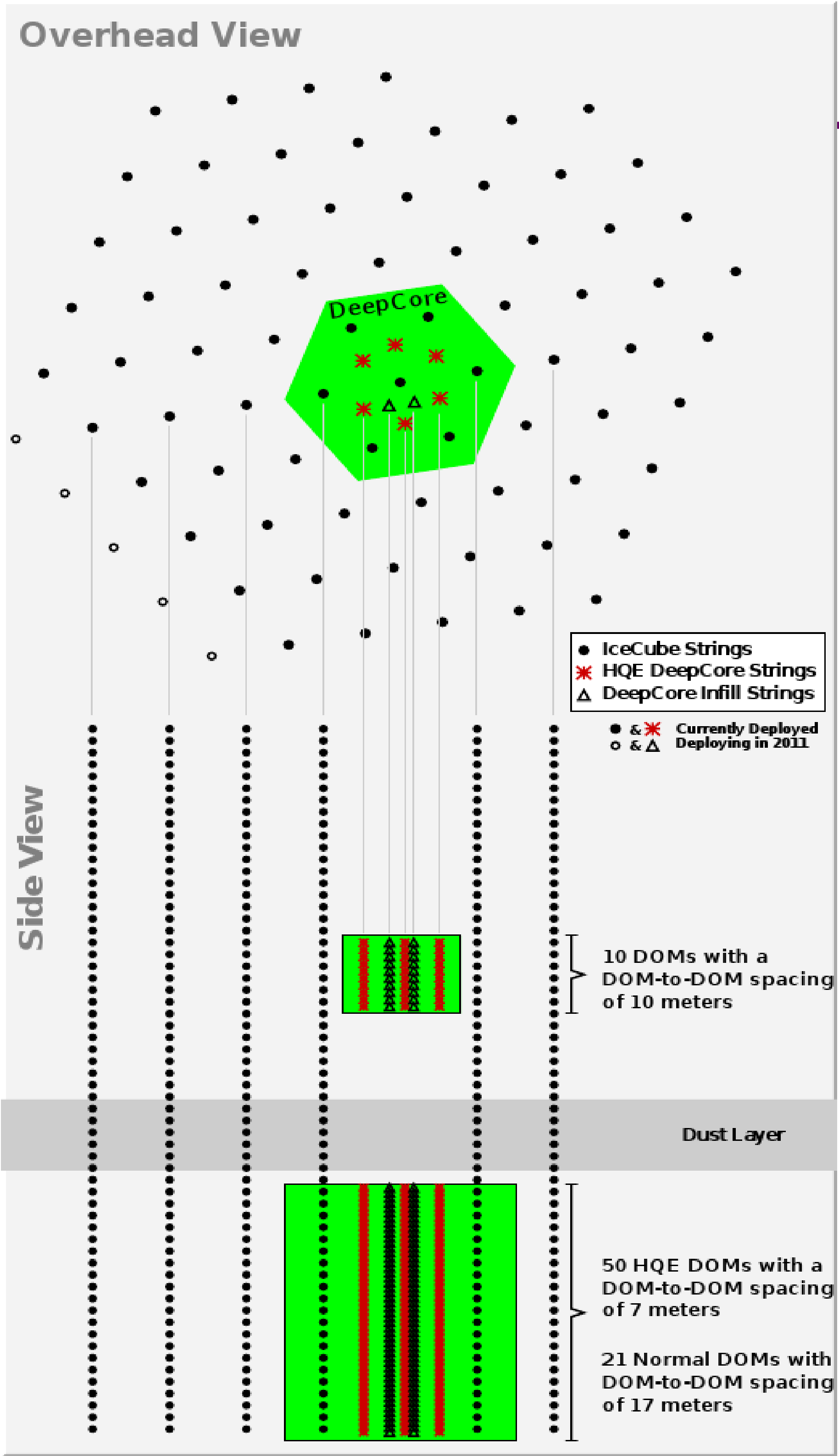




The **measured gamma ray spectrum** allows to estimate the **neutrino spectrum**, in the case that they are produced in proton-proton interactions *[astro-ph]arxiv: 0607286 (2007).*

How to open the field of view of IceCube to the Southern Hemisphere for Galactic Neutrino Sources with a soft-spectrum?

$$\frac{dN}{dE_\nu} = 15.52\left(\frac{E_\nu}{1\,TeV}\right)^{-1.72} e^{-\sqrt{\frac{E_\nu}{1.35}}}\, 10^{-12}\, TeV^{-1}.cm^{-2}.s^{-1} \quad .$$



The DeepCore detector

- 15 strings/ 60 DOMs each:
  - 6 strings **with 40% higher quantum efficiency**
  - 7 surrounding IceCube strings.
  - 2 infill strings with standard IceCube PMTs
- **Denser spacing**: ~70m between the strings
  ~7m between the DOMs
- **Very clear ice** (twice as clear as the average ice in the upper part of IceCube)

➔ Larger number of photons are recorded.
➔ Improved reconstruction at low energies

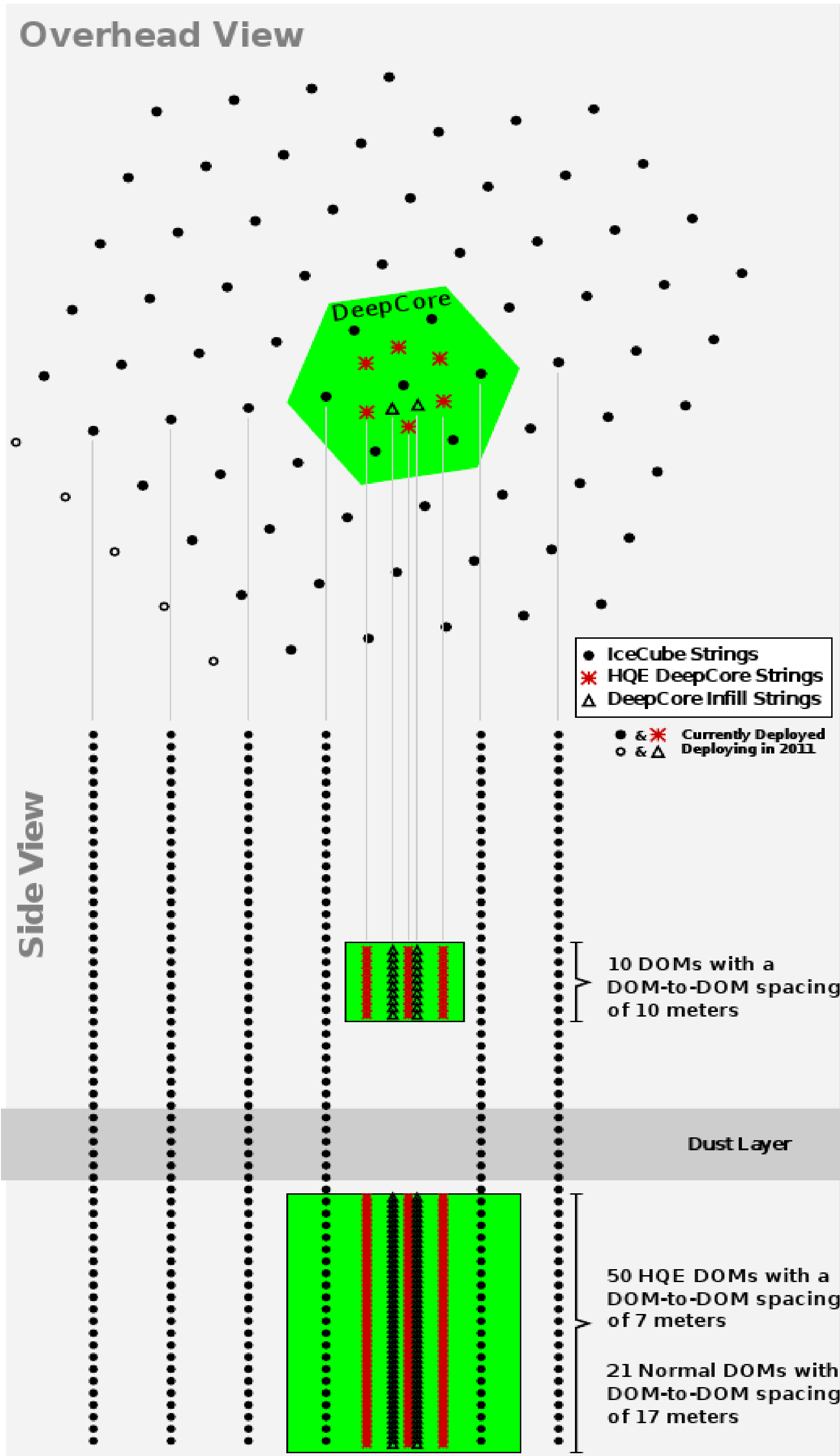
- Currently deployed: 7 strings.

  The two infill strings will be deployed in the Austral summer 2010/2011.

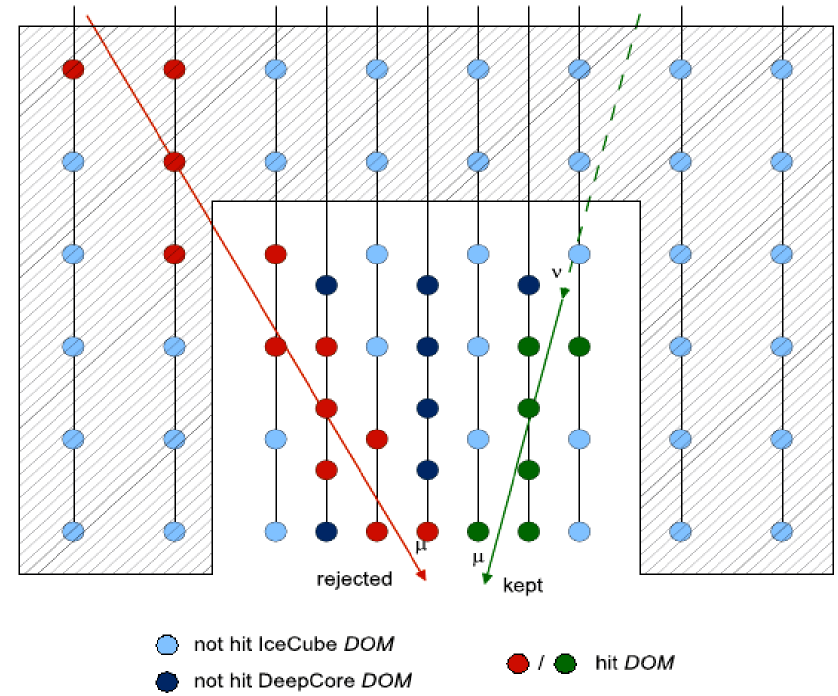
Purpose:

- Enhance the sensitivity of IceCube for **low energies** (< 100 TeV).
- Lower the detection threshold of IceCube by an order of magnitude to energies **as low as 10 GeV**.

The Atmospheric muon Veto



Veto atmospheric muons while keeping a good passing rate of starting neutrinos.



Events with hits in the veto region (shaded) are treated as atmospheric muon background. Events with hits in the fiducial region are signal.

Fiducial Volume: cylinder around **String 36**. **R=200m**, **H=350m** (6 DC strings + 7 surrounding IC strings + 2 infill IC strings.)

Atmospheric muon Veto: L1 & L2 cuts

- **Level 1 cuts** aim to reduce the atmospheric background for 3-4 orders of magnitude, before reconstruction, using only the topology of the hits.

→ Keep events with **hits only in the *Fiducial Volume***

→ Background rejection: **~ 5 x 10^{-4}**

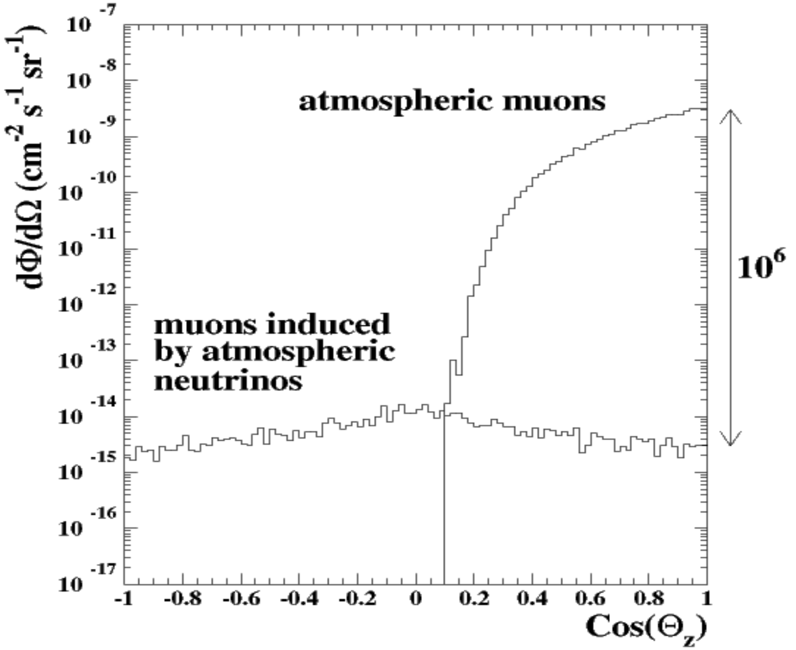
- **Level 2 cuts** are based on the output of the vertex reconstruction algorithm.

• **LLHR** – Likelihood for the track to be starting inside the Fiducial Volume.

• The reconstructed vertex position is described by the **Z-coordinate** and the **radius R** from the center of DeepCore:

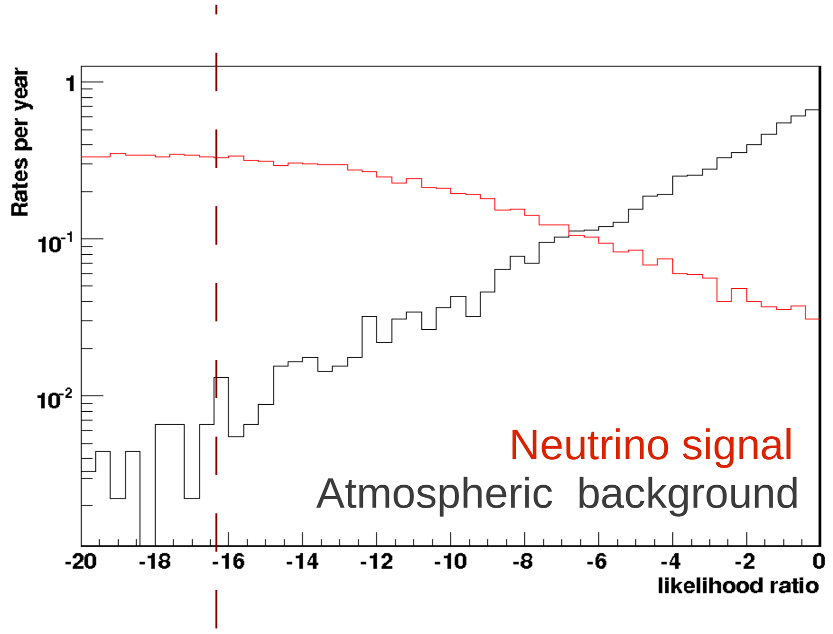
$$LLHR = \frac{\mathrm{P(nohit|external)}}{\mathrm{P(nohit|internal)}}$$

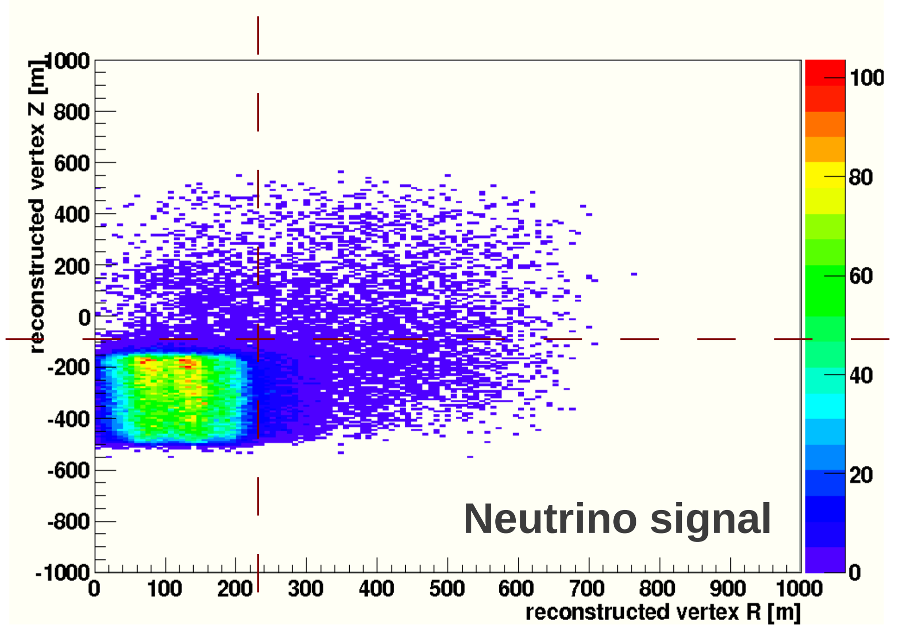
$$R = \sqrt{\left(X_{vertex} - 46\mathrm{m}\right)^2 + \left(Y_{vertex} + 34.5\mathrm{m}\right)^2} \ .$$



Atmospheric Muon Veto L2 Cuts: Optimization for Point Source search

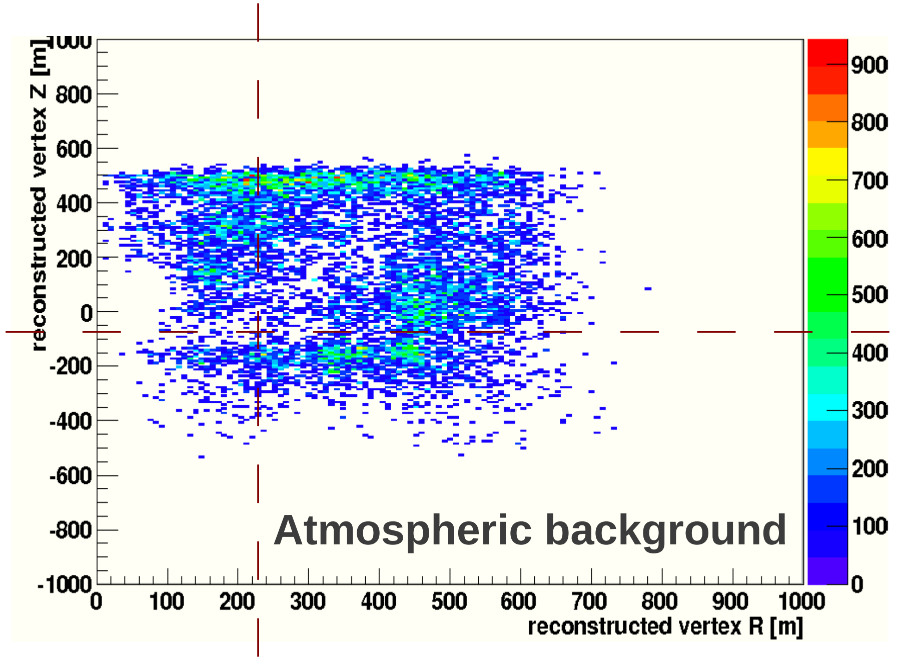
Reject the maximum number of atmospheric muon background while keeping the maximum number of signal events starting inside IceCube-DeepCore.





R < 180m, Z < -210 and LLHR < -16

Background rejection: **10^{-6}**
Signal passing rate: ~ 50%



$$Purity = \frac{Signal}{Signal + Atmospheric\,muon\,background} > 98\%$$

Atmospheric neutrino veto

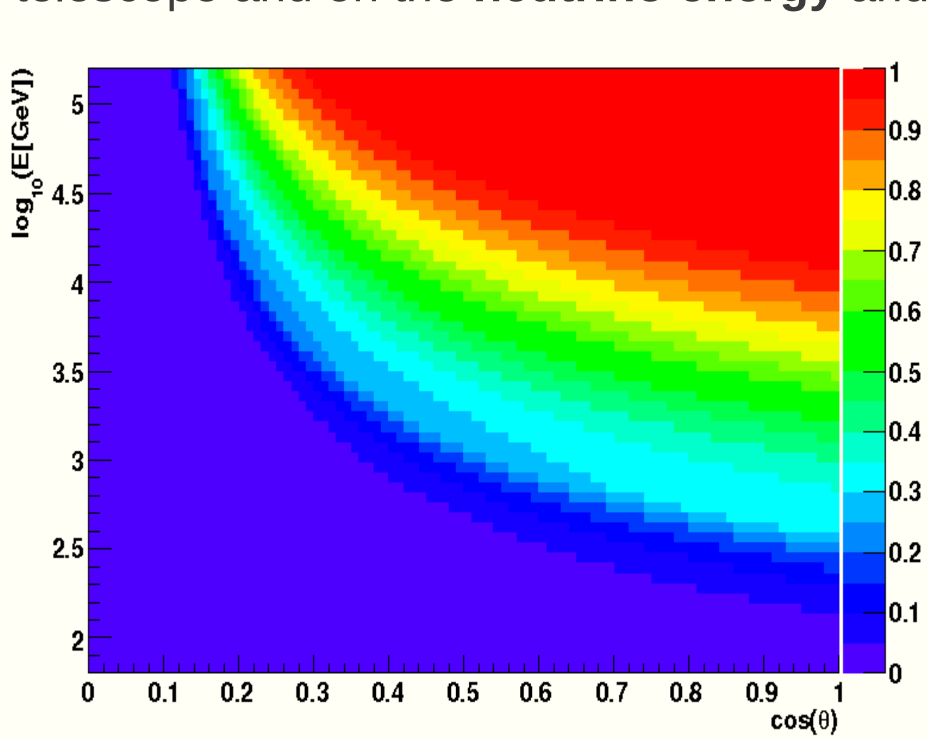
Phys.Rev.D79,043009 (2009) [astro-ph]: 0812.4308, S.Schonert et al.

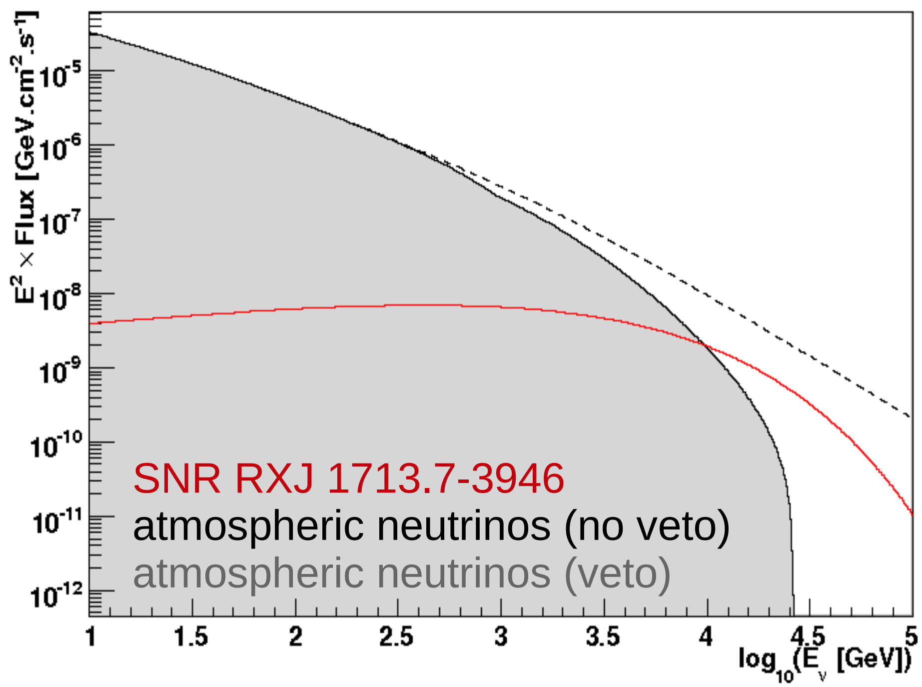
- At **Tev-PeV energies**, the opening angle between a downward-going atmospheric ν_μ and the μ produced by the decay of the same parent meson in the atmosphere is very small.

→ a downward-going atmospheric ν_μ has a **certain probability** to reach the detector accompanied by its partner μ .

→ veto a downward-going atmospheric ν_μ by the detection of a correlated atmospheric μ.

- The veto performances depend on the **atmospheric muon veto** efficiency, the **depth** of the telescope and on the **neutrino energy** and **direction**.





Point-source analysis: SNR RXJ 1713.7-3946

- **Monte Carlo simulations** with **IceCube 80-strings** and **DeepCore 6-strings** configurations.
- Keep events in a **zenith band of width 10º** around the source.

→ Signal: Muon-neutrinos starting inside DeepCore (IceCube Neutrino Generator): *2800 events.*

→ Background***:*** atmospheric muons (CORSIKA) *< 2 events*.
atmospheric neutrinos (*conventional flux, HONDA 2006*) *< 2250 events.*

→ Signal events are distributed according to:

$$\frac{dN}{dE_\nu} = 15.52 \times \left(\frac{E_\nu}{1\,TeV}\right)^{-1.72} e^{-\sqrt{\frac{E_\nu}{1.35}}}\, 10^{-12}\, TeV^{-1}.cm^{-2}.s^{-1} \quad .$$

Source PDF:

$$S_i = \frac{1}{2\pi\sigma^2} e^{\frac{-|\vec{x}_i - \vec{x}_S|}{2\sigma^2}}$$

Track reconstruction algorithms are under development:

Approximated angular resolution of DeepCore:
σ= 2º (*consistant with preliminary results from reconstruction*)

Neutrino energies considered: ***100 GeV < E_ν < 1 PeV***.

Unbinned Likelihood Ratio method

J. Braun et al., Astropart.Phys.29:299-305 (2008)

- The events are given a probability to belong to the source with a certain uncertainty **σ**.

$$S_i = \frac{1}{2\pi\sigma^2} e^{\frac{-|\vec{x}_i - \vec{x}_S|}{2\sigma^2}}$$

Source PDF with **σ**: DeepCore angular resolution (***2º***)

- The probability for an event to be an atmospheric background event is given by:

$$B_i = \frac{1}{\omega_{band}}$$

Background PDF with **ω**: solid angle of the zenith band.

- The **Likelihood** for a source to be at location Xs with a strength Ns is therefore:

$$L = \prod_N \frac{N_S}{N} S_i + \left(1 - \frac{N_S}{N}\right) B_i$$

N: total number of events (signal + background)

- The likelihood L is maximized to obtain the best estimate of the number of signal events.

Test Statistic & Significance

- The events are Poisson-distributed around a mean source strength: **$\langle N_S \rangle$ = [-10; 40]** events.

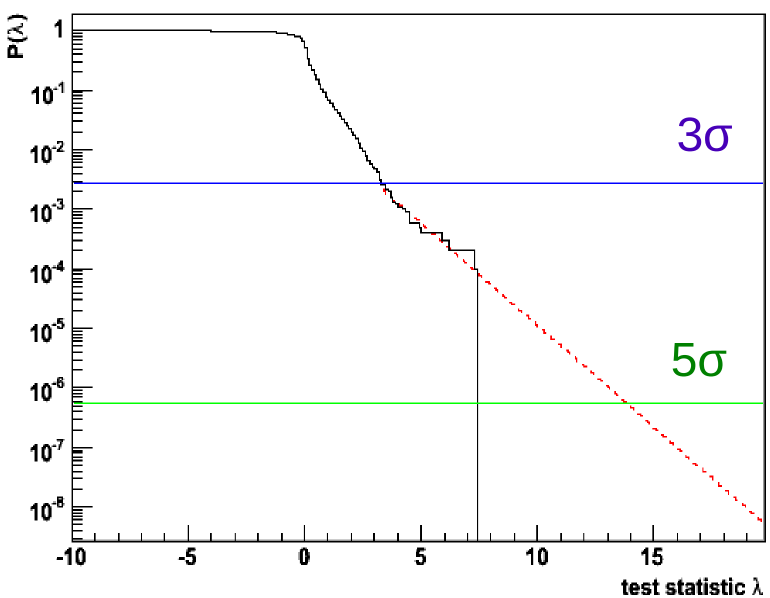
→ Scale the flux model by a factor **FLUXSCALE**.

- Signal + Background simulation: **1000** experiments for each **FLUXSCALE**.

- Background alone:**10000** experiments with randomized azimuth.

- For each experiment we record the **test statistic λ** to determine the significance of a deviation from the null hypothesis H0:.

$$\lambda = -2.\mathrm{sign}(\hat{N}_S).\log\frac{L(\vec{X}_S, 0)}{L(\vec{X}_S, \hat{N}_S)}$$



λ3σ = 3.4 **λ5σ = 13.9**

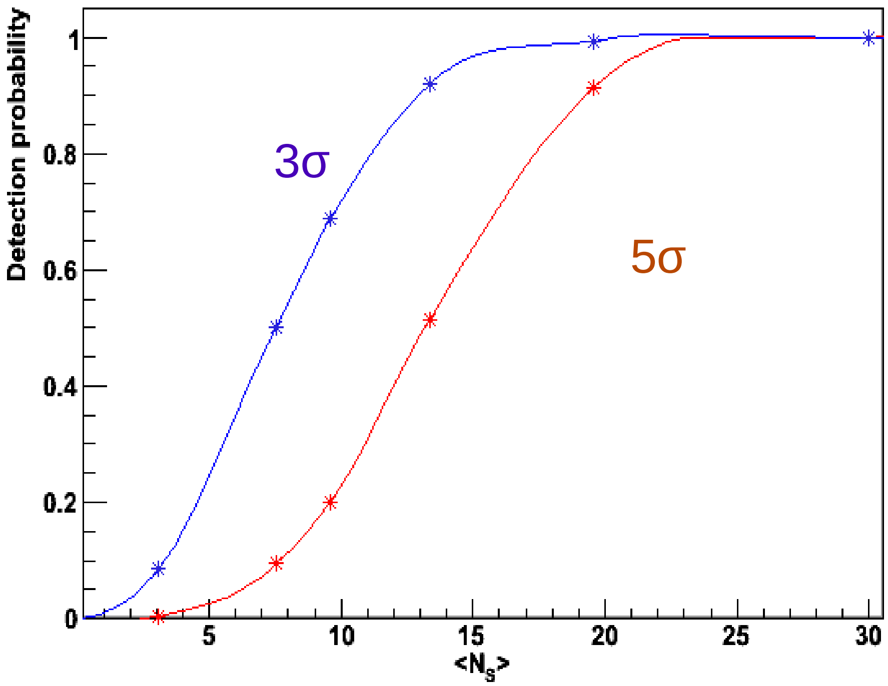
$H_0 = L(\vec{X}_S, 0)$: The data consists of background events.

$H_S = L(\vec{X}_S, \hat{N}_S)$: The data consists of $\hat{N}_S$ signal events from the source and background events.

The **discovery potential at 3σ and 5σ** are the number of experiments with λ above the 3σ and 5σ threshold, respectively.

Discovery Fluxes: SNR RXJ 1713.7-3946

- 3σ and 5σ confidence level **detection probability** vs. Poisson mean number of source signal events (atmospheric muon background rejection: 10^{-6}).



Number of signal events needed on top of the background to achieve a **50% chance of detection** at the 3σ and 5σ C.L.:

$$\left\{ \begin{array}{l} \bar{\mu}(50\%, 3\sigma) = 7.656\ events \\ \bar{\mu}(50\%, 5\sigma) = 13.17\ events \end{array} \right. .$$

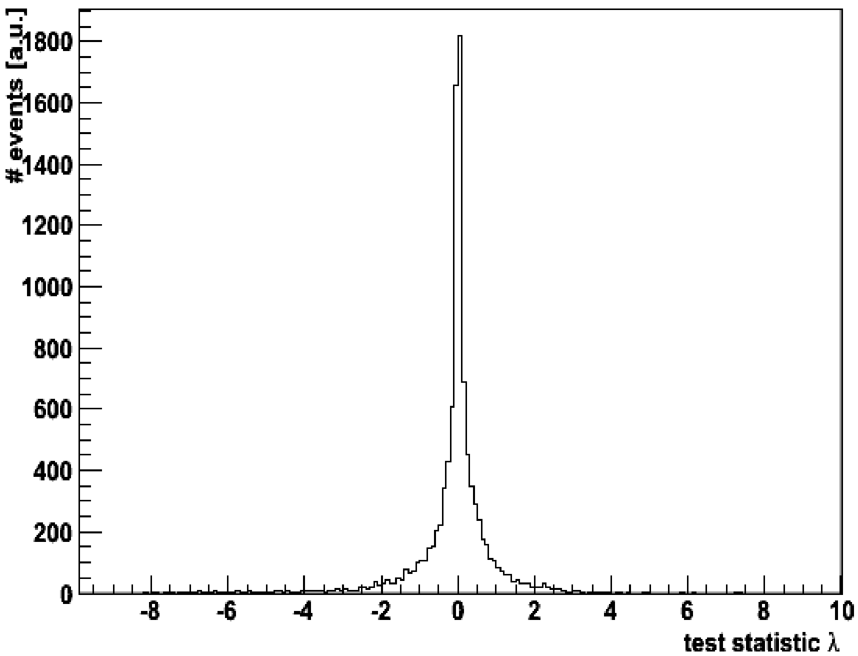
<u>DISCOVERY FLUXES (after one year)</u>:

$$\phi_{50\%,3\sigma} \leq 4.00 \times 15.52 \times E^{-1.72} \times e^{-\sqrt{E/1.35}} \times 10^{-10}\, TeV^{-1} \cdot cm^{-2} \cdot s^{-1}$$

$$\phi_{50\%,5\sigma} \leq 6.96 \times 15.52 \times E^{-1.72} \times e^{-\sqrt{E/1.35}} \times 10^{-10}\, TeV^{-1} \cdot cm^{-2} \cdot s^{-1}$$

Sensitivity to SNR RXJ 1713.7-3946

Neyman 90% C.L. Upper Limit (*Amsler et al. 2008*)



Distribution of λ for background alone

$\lambda_{Median} \sim 0.00$

<u>Neyman-Pearson lemma:</u>

Reject H_0 if $P(\lambda > \lambda_{Median} \mid H_0) = 90\%$

H_0 – Null hypothesis.

The data consists only of background

H_1 – The data consists of signal and background.

μ90% = 5.86 events

<u>Sensitivity at the 90% C.L (after one year)</u>:

$$\phi_{90\%} \leq 2.84 \times 15.52 \times E^{-1.72} \times e^{-\sqrt{E/1.35}} \times 10^{-10}\, TeV^{-1} \cdot cm^{-2} \cdot s^{-1}$$

Enhancement of the Sensitivity (after one year, at the 90% C.L.)

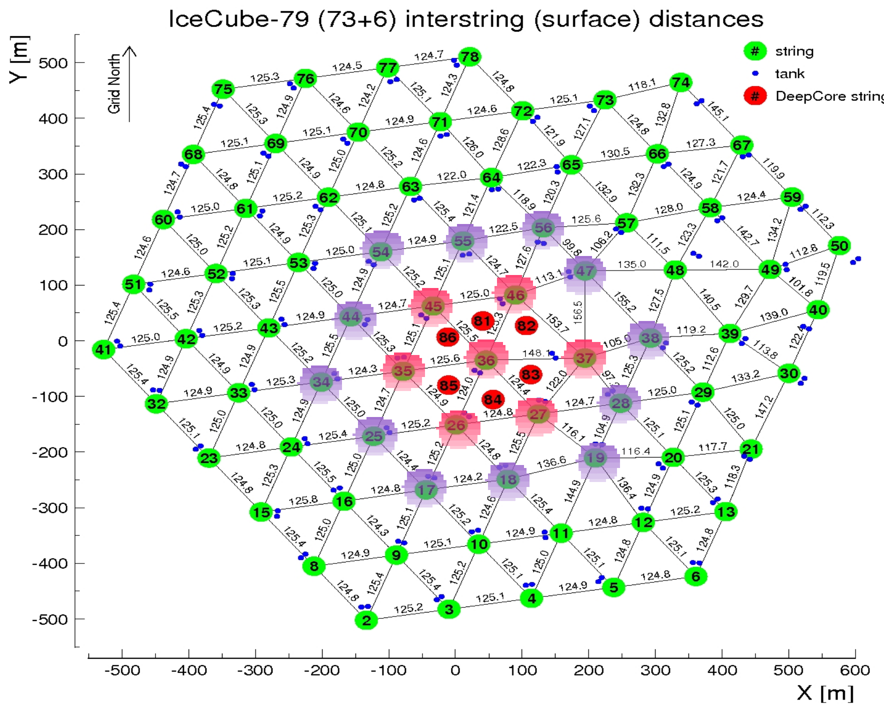
(1) → **(2):** Relaxation of the μ_{Atmo} Veto cuts:

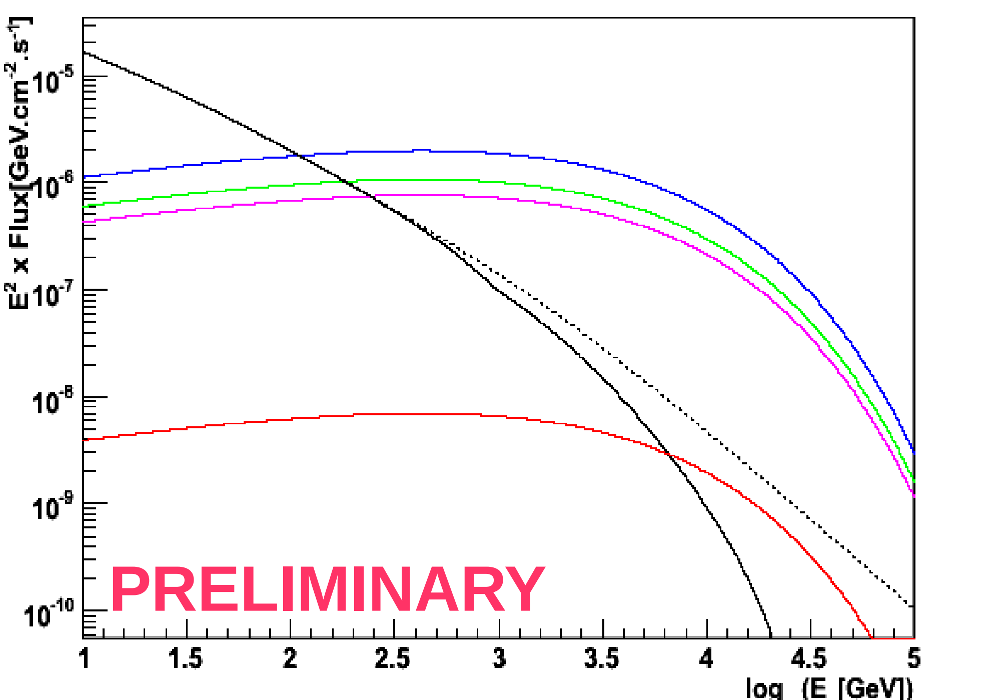
- Background rejection of 10^{-5}
- Passing rate of starting neutrinos: 85%

→ Sensitivity enhanced by a **factor of ~ 2**.

(2) → **(3):** Increase horizontally the Fiducial Volume:

→ Sensitivity enhanced by a **factor of ~1.5**.





(1) $\phi_{90\%} \leq 2.84 \times 15.52 \times E^{-1.72} \times e^{-\sqrt{E/1.35}} \times 10^{-10}$

(2) $\phi_{90\%} \leq 1.53 \times 15.52 \times E^{-1.72} \times e^{-\sqrt{E/1.35}} \times 10^{-10}$

(3) $\phi_{90\%} \leq 1.09 \times 15.52 \times E^{-1.72} \times e^{-\sqrt{E/1.35}} \times 10^{-10}$

expected signal flux

atmospheric neutrino flux (no veto)

atmospheric neutrino flux

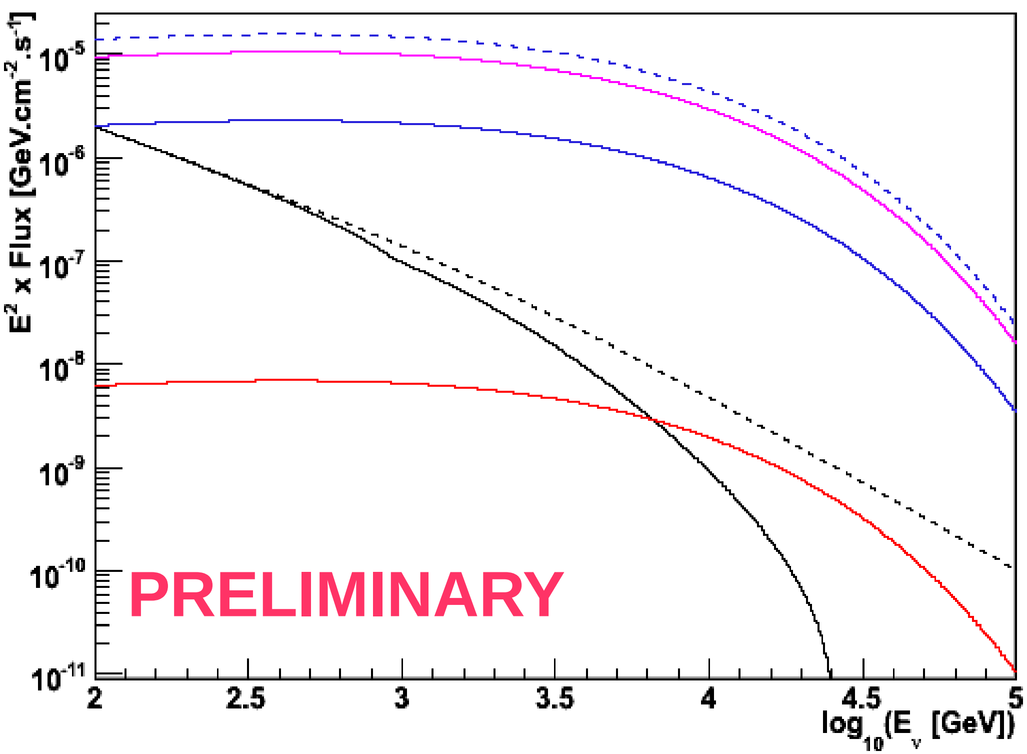
Comparison ANTARES vs IceCube-DeepCore Discovery Potential at 5σ

Calculations for ANTARES have been made by A. Kappes (from *[astro-ph]arXiv:0607286*):

- Use of an ANTARES old effective area which is not *zenith dependent* (*Brunner et al., 2005*)
- *It is assumed that all atmospheric muons can be suppressed.*
- *Assumed angular resolution: 0.4° for energies between **10 GeV and 1 PeV**.*

<u>Discovery potential of ANTARES to the SNR RXJ 1713.7-3946 (after 1 year)</u>:

$$\phi_{50\%,5\sigma} \leq 15 \times 15.52 \times E^{-1.72} \times e^{-\sqrt{E/1.35}} \times 10^{-10}\, TeV^{-1} \cdot cm^{-2} \cdot s^{-1}$$



(1) DeepCore (**10 GeV < E < 1 PeV**)

(2) DeepCore (this analysis)

(3) ANTARES (**10 GeV < E< 1 PeV**)

expected signal flux

atmospheric neutrino flux (no veto)

atmospheric neutrino flux

CONCLUSIONS and OUTLOOK

- An **innovative** and **exploratory approach** to Neutrino Astronomy is under development to observe steady soft/hard-spectra **galactic neutrino sources**.

- A **very preliminary** sensitivity to the **benchmark source *RXJ 1713.7-3946*** has been presented.

- The **atmospheric muon veto** and **IceCube-DeepCore** can be used to open the field of view of IceCube to the Southern Hemisphere below 1 PeV.

- The **atmospheric neutrino veto** can be used to discriminate part of the source signal (depending on the source location and the neutrino energy) from the background of atmospheric Neutrinos.

- By using **DeepCore as an active veto** (against atmospheric muons and neutrinos) the discovery potential/sensitivity of DeepCore to the SNR RXJ 1713.7-3946 **becomes comparable** with the discovery potential/sensitivity of ANTARES.

NEXT STEPS

- Develop dedicated **simulations** (based on CORSIKA) to assess the **atmospheric neutrino veto** capability in practice.

- Study the impact of the atmospheric neutrino veto on the discovery potential/sensitivity as a function of the energy.

- Include muon track and energy **reconstruction algorithms**.

  → Determine IceCube-DeepCore angular resolution as a function of the energy.

- Include **energy term in the likelihood** maximization (expected improvement of about **30%**) as described in ***J.Braun et al., Astroparticle Physics 29 (2008) 299-305***

- Estimate the sensitivity to **other astrophysical objects of interest** (H.E.S.S. SNRs, Galactic Center region) throughout the Southern Hemisphere.

- Investigate **potential extensions of *IceCube-DeepCore*** to enhance the sensitivity.

- **Analysis of the first data** from the 79 strings configuration of IceCube-DeepCore (Spring 2011).

- Investigate new strategies to **combine the data recorded by ANTARES and DeepCore**

Thank you!

EXTRA SLIDES

Test Statistic

- The events are Poisson-distributed around a mean source strength: **$\langle N_s \rangle$ =** **0 - 40 events.**

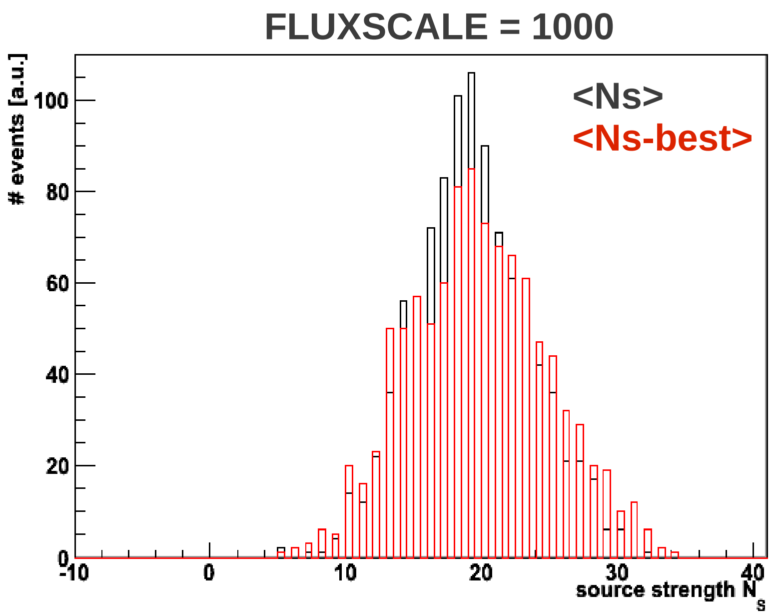
→ Scale the flux model by a factor **FLUXSCALE**.

- Downward fluctuations of the background:

$$-10 < N_s < 40$$

- Signal + Background simulation: **1000** experiments for each **FLUXSCALE**.

- Background alone:**10000** experiments with randomized azimuth.



- For each experiment we record the **test statistic λ** to determine the **significance** of an observed deviation from the null hypothesis.

$$\boxed{\lambda = -2.\mathrm{sign}(\hat{N}_S).\log\frac{L(\vec{X}_S, 0)}{L(\vec{X}_S, \hat{N}_S)}}$$

$H_0 = L(\vec{X}_S, 0)$ The data consists only of background events.

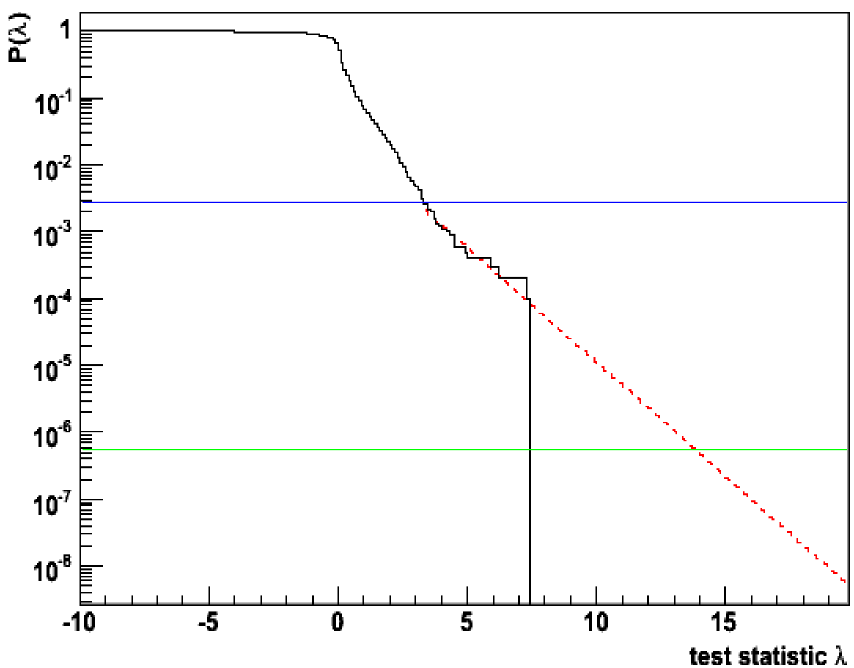
$H_S = L(\vec{X}_S, \hat{N}_S)$ The data consists of $\hat{N}_S$ signal events from the source and background events.

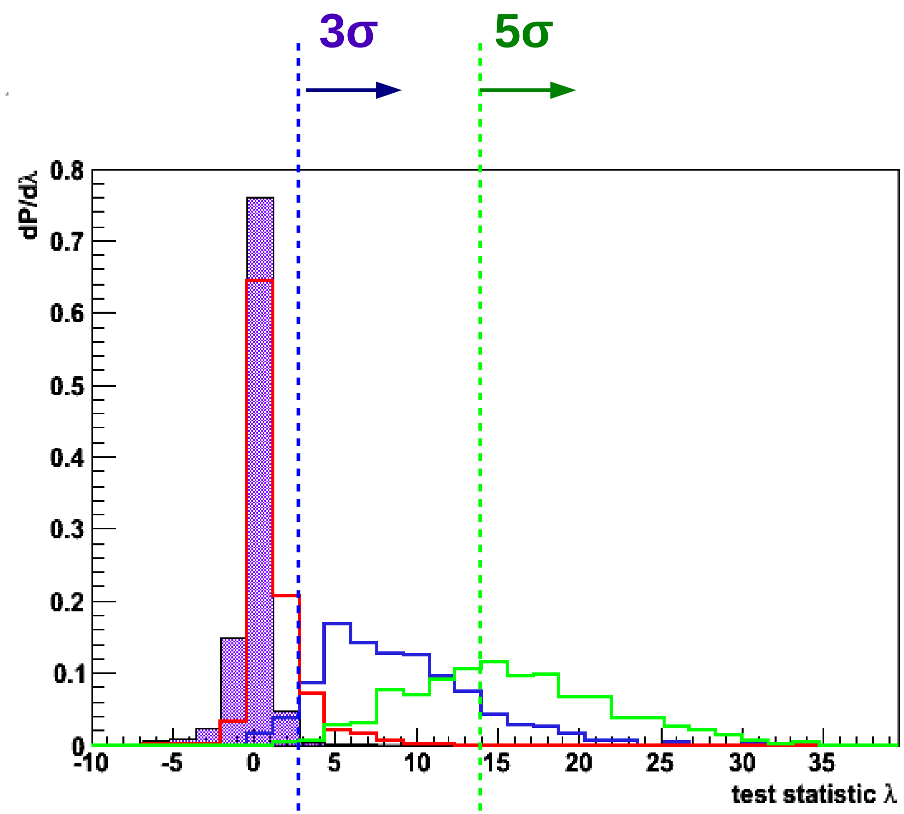
Significance and discovery potential

Procedure

3σ

5σ





λ = 3.4 **λ = 13.9**

λ = 3.4 **λ = 13.9**

- The integral distribution of λ for the background alone is calculated at the location of the source.

- The values of λ corresponding to 3σ and 5σ are calculated.

- The discovery potential at 3σ and 5σ are the number of experiments with λ above the 3σ and 5σ threshold, respectively.

PROPOSAL

Combined analysis: IceCube-DeepCore and ANTARES.

Opening the field of view of **IceCube** to the Southern Hemisphere allows an overlap with **neutrino telescopes of the Northern Hemisphere**.

→ Investigate new strategies for combining the data collected by I**ceCube-DeepCore** and **ANTARES**.

Motivations:

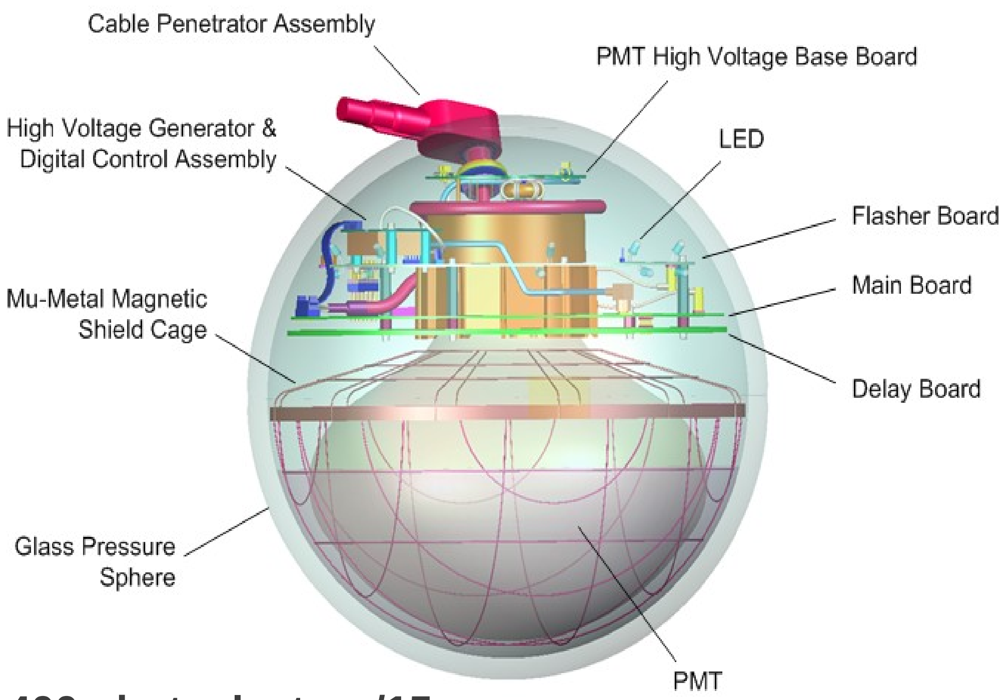
- **Enhance the sensitivity** to the signal coming from soft-spectra Galactic Neutrino Sources.

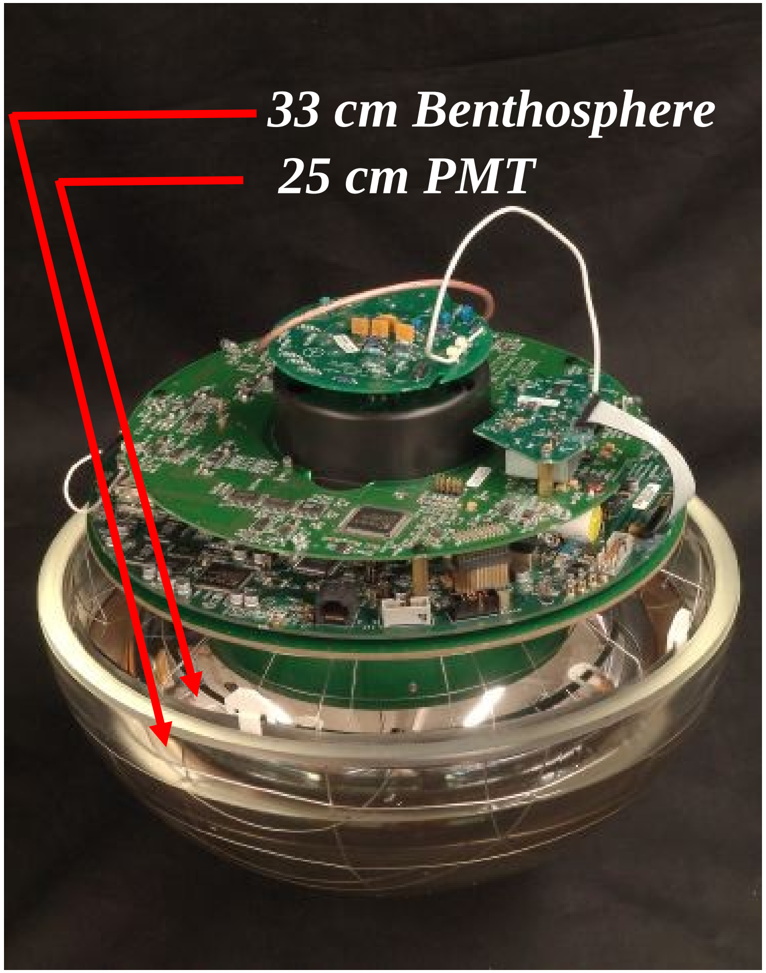
- The systematic errors involved in both telescopes differ, in particular due to the different media in which they are deployed.

→ By combining both telescopes such **systematics could be avoided** or at least consequently reduced.

IceCube Digital Optical Module

Waveforms, times digitized in each DOM



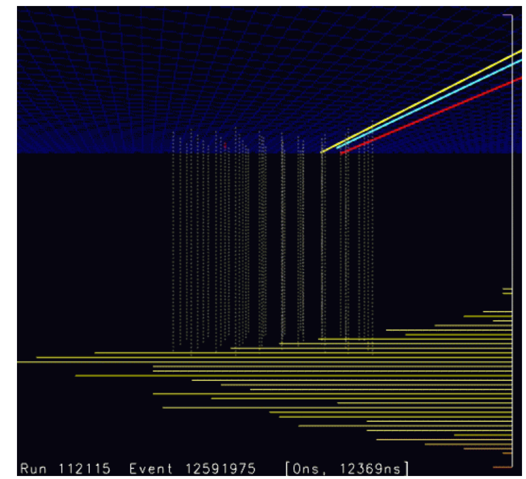


- **400 photoelectron/15ns**
- **400ns/6.4µs time range**

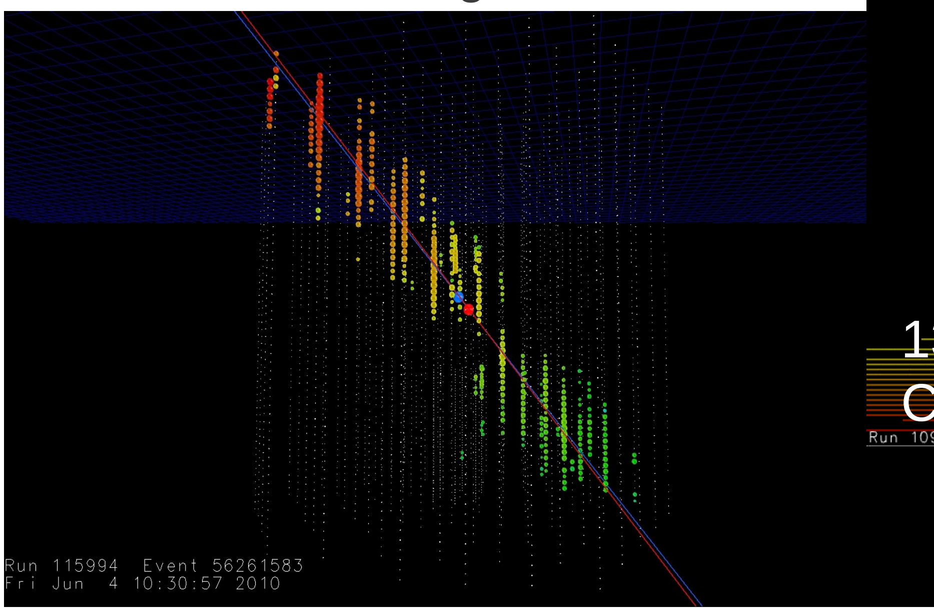
IceCube Event Gallery

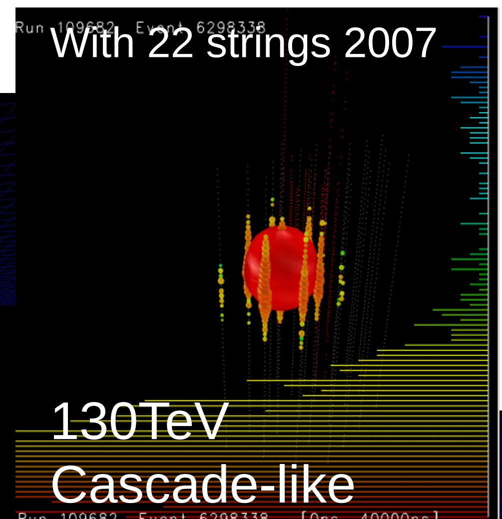
Cherenkov light illuminations from particles 01752060123

With 40 strings, 2008 Dec

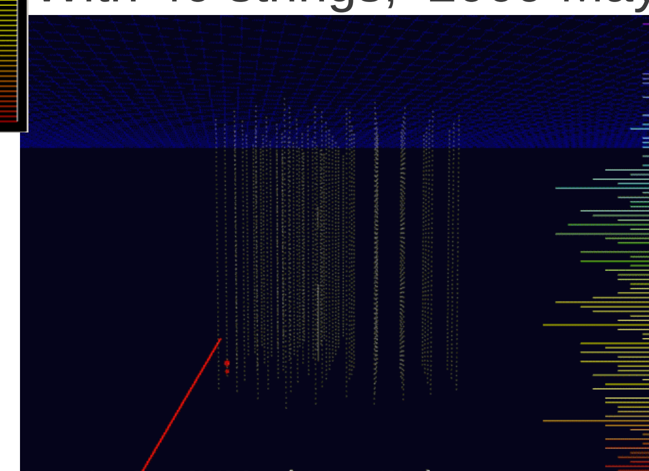


With 79 strings, 2010 June





With 40 strings, 2009 May



Energy threshold ~10 GeV
>10^8 muons/day
>200 neutrinos/day