NEUTRINO TELESCOPE RESULTS

ICECUBE & ANTARES

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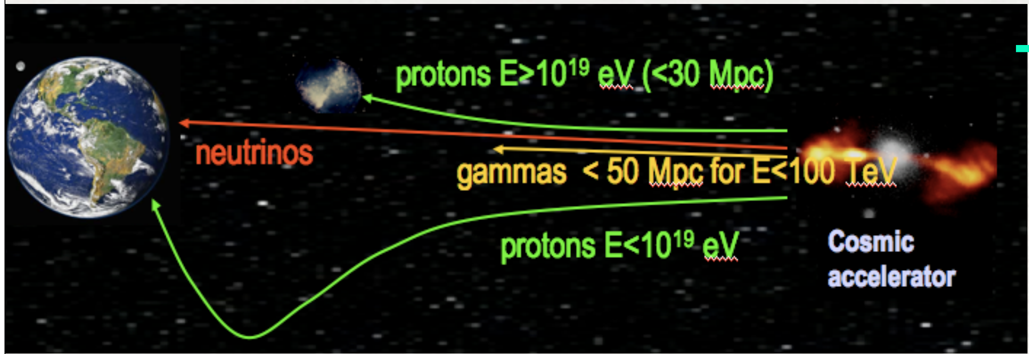
Neutrino Astronomy: why?
The Cosmic ray connection
Gamma and Proton
Astronomy connections
Candidate sources

Messengers from the Universe

Travel distance depends on interactions on radiation backgrounds once particles exit sources



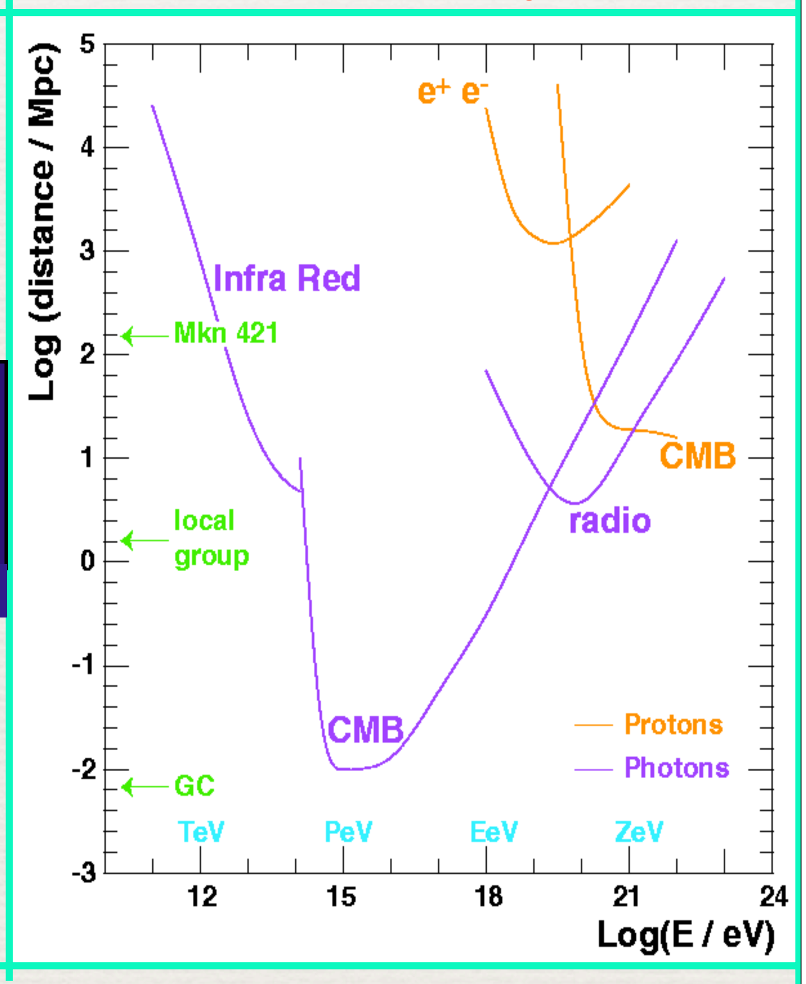
absorption		cut-off	mean free path
γ-rays:	$\gamma + \gamma_{2.7k}$	$>10^{14}$eV	10 Mpc
proton:	$p + \gamma_{2.7k} \rightarrow \pi^0 + X$	$>5.10^{19}$eV	50 Mpc
neutrinos:	$\nu + \nu_{1.95K} \rightarrow Z+X$	$>4.10^{22}$eV	(40 Gpc)

neutrons decay: $\Upsilon ct = E/m\ ct \sim 10$ kpc for E ~ 10^{18} eV

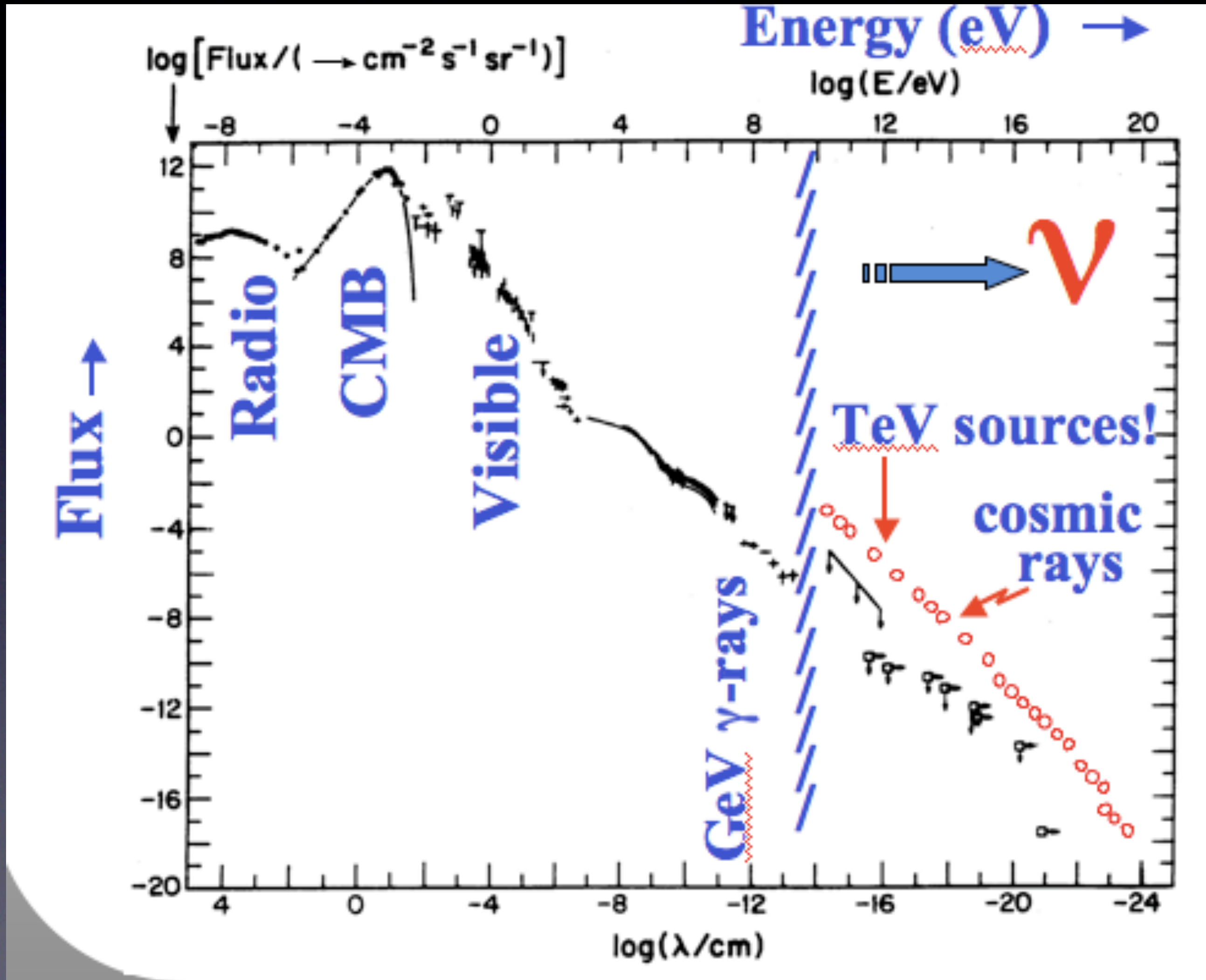
Galactic Centre	8 kpc
Local group (Andromeda M31)	0.725 Mpc
Mrk 421	~ 136 Mpc

Universe c/H_0 = 13.7 billion yrs (WMAP) ~ 4000 Mpc

1Mpc = 3.26 Mly = 3.1 10^{24} cm



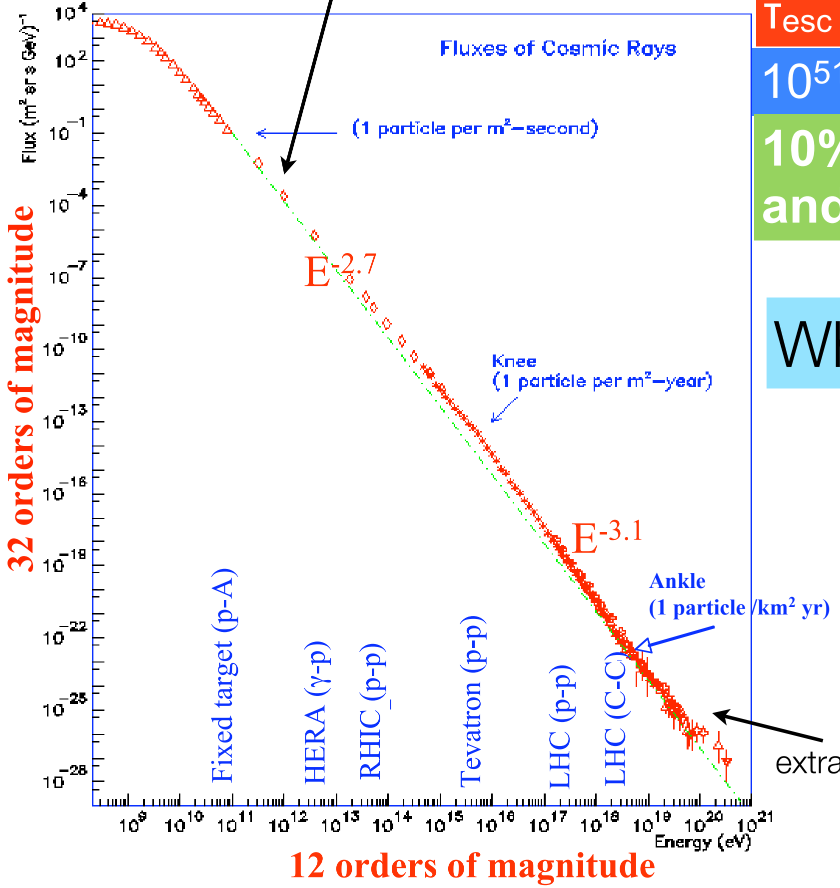
Photons, CRs and Neutrinos



Cosmic Ray Spectrum

1 TeV = 1.6 erg
1 EeV = 0.16 Joule

galactic



extra-galactic

Below the knee observed energy density of galactic CR: $\rho_E \sim 10^{-12}$ erg/cm^3
Power needed: $\rho_E / \tau_{esc} \approx 10^{-26}$ erg/cm^{3}s
$\tau_{esc} \approx 3\times10^6$ yrs escape time from Galaxy

10^{51} erg/SN every 30 years$\sim 10^{-25}$ erg/cm^3 s

10% of SN provides the environment and energy to explain the galactic CRs!

What sources for $>10^{17}$ eV CRs?

observed energy density of extra-gal CRs:
$\sim 3 \times 10^{-19}$ erg/cm^3

$\sim 6 \times 10^{44}$ erg/yr/Mpc^3 for 13.7 Gyrs

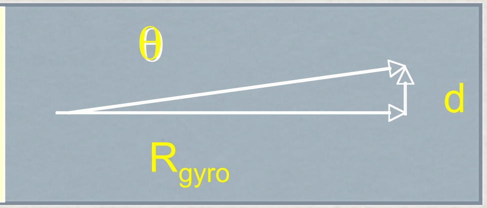
Gamma-Ray Bursts:
2×10^{51} erg x 300/yr/Gpc^3 = 6×10^{53} erg/yr/Gpc^3
$\sim 6 \times 10^{44}$ ergs/yr/Mpc^3

Auger result: hint for closeby AGNs?

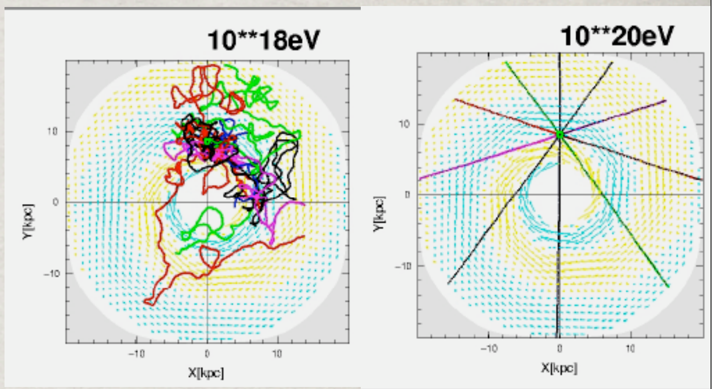
Proton Astronomy

Astronomy messengers need to point back to their sources

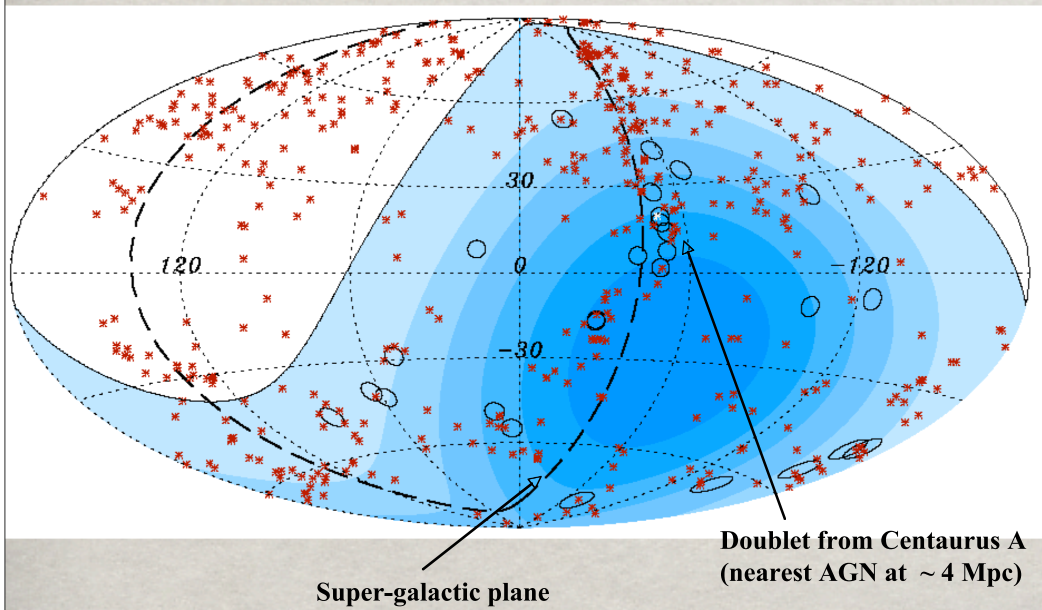
$$\vartheta \cong \frac{d}{R_{gyro}} = \frac{dB}{E} \Rightarrow \frac{\vartheta}{0.1^\circ} = \frac{\left[\frac{d}{1Mpc}\right]\left[\frac{B}{1nG}\right]}{\left[\frac{E}{3\times10^{20}\,eV}\right]}$$



Protons of 300 EeV are deflected about 0.1° in 1 Mpc
but uncertainties on magnetic fields are high



Pierre Auger Observatory Science, Nov 2007

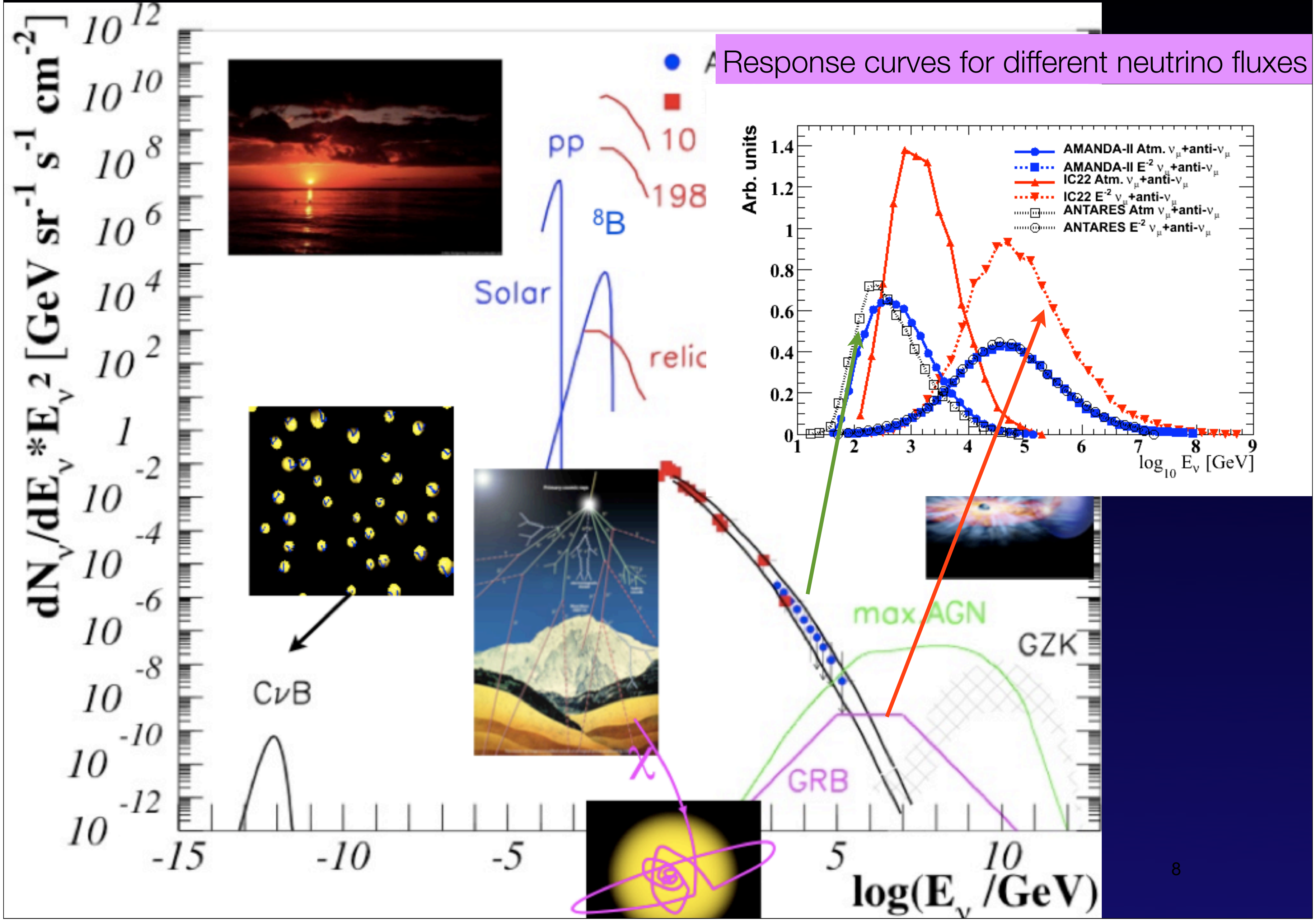


20/27 events with E>57 EeV correlate with an incomplete catalogue of 292 AGN (<71 Mpc) within 3.1°.
Isotropy incompatible at 1% level.

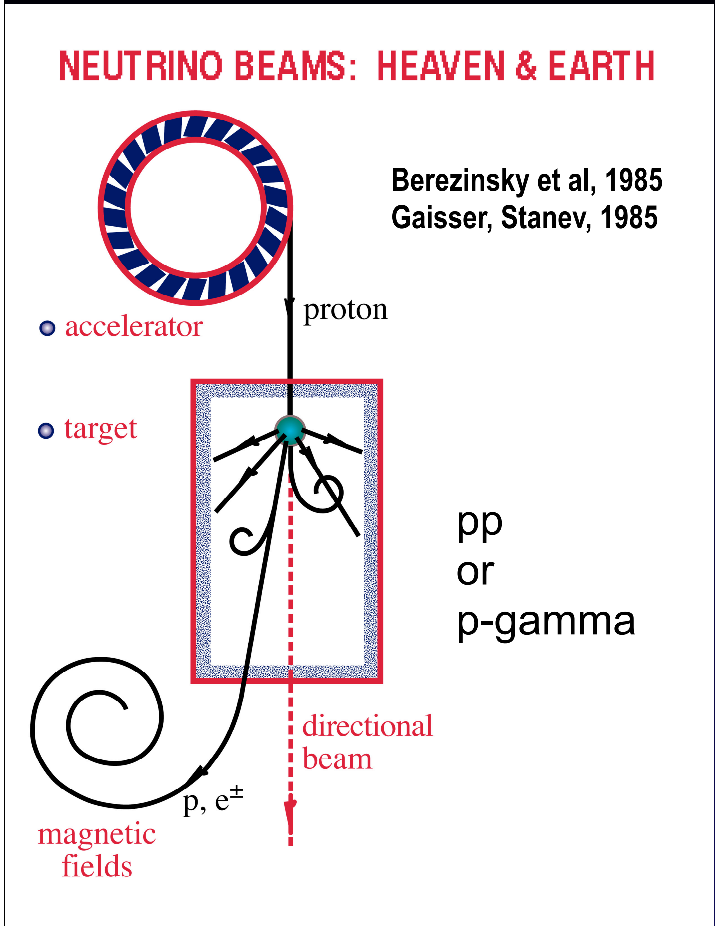
Open problems:
X_{max} hints for heavy composition > 2 EeV
=> larger deflection in B fields
HiRes does not confirm (arXiv:0804.0382)
No events from Virgo while same number as from Cen A would be expected

Neutrino fluxes

Response curves for different neutrino fluxes



The generic Neutrino source



pions share p energy

$p + A \rightarrow \pi^0 \quad \pi^+ \quad \pi^-$

$\pi^0 \rightarrow \gamma \; \gamma \qquad \pi^+ \rightarrow \nu \; \mu^+ \qquad \pi^- \rightarrow \nu \; \mu^-$

$E_\pi \sim E_p/3$

2 photons with

$$E_\gamma \approx E_\pi/2 \approx E_p/6$$

$e^+ \; \gamma$

For each gamma 2 ν_μs with:

$$E_\nu \approx E_\pi/4 \approx E_p/12$$

$\mu^+ \rightarrow e^+ \; \nu \; \nu$

$$E_p^{min} = \Gamma \frac{(2m_p + m_\pi)^2 - 2m_p^2}{2m_p}$$

$$p + p \rightarrow p + p + \pi^0$$
$$p + p \rightarrow p + n + \pi^+$$

Hence energy in photons and neutrinos is the same.

$$\nu_e : \nu_\mu : \nu_\tau = 1:2:0 \xrightarrow{oscillations} 1:1:1$$

After oscillations: $\nu_\mu/\gamma \sim 0.5$

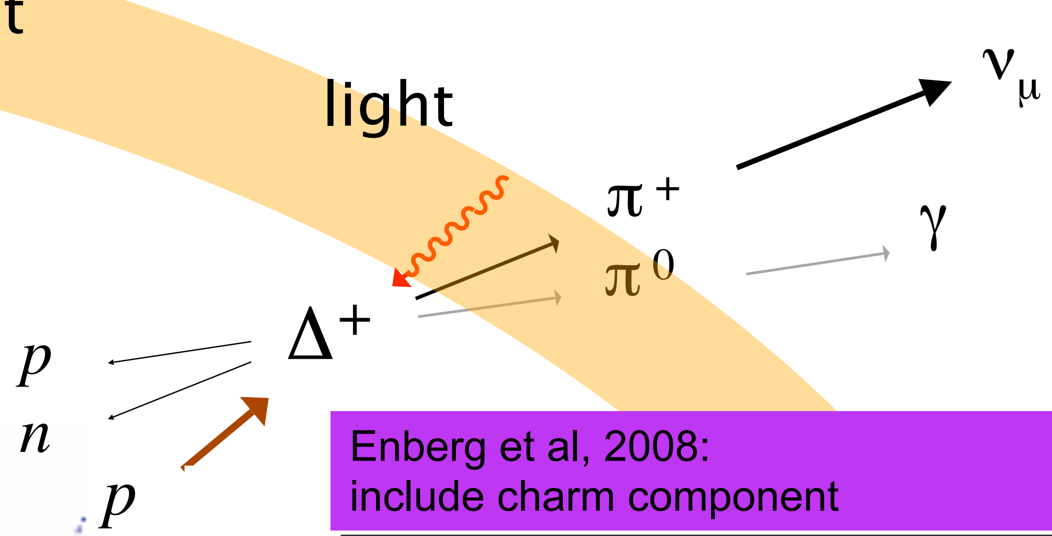
Gamma-Astronomy connection

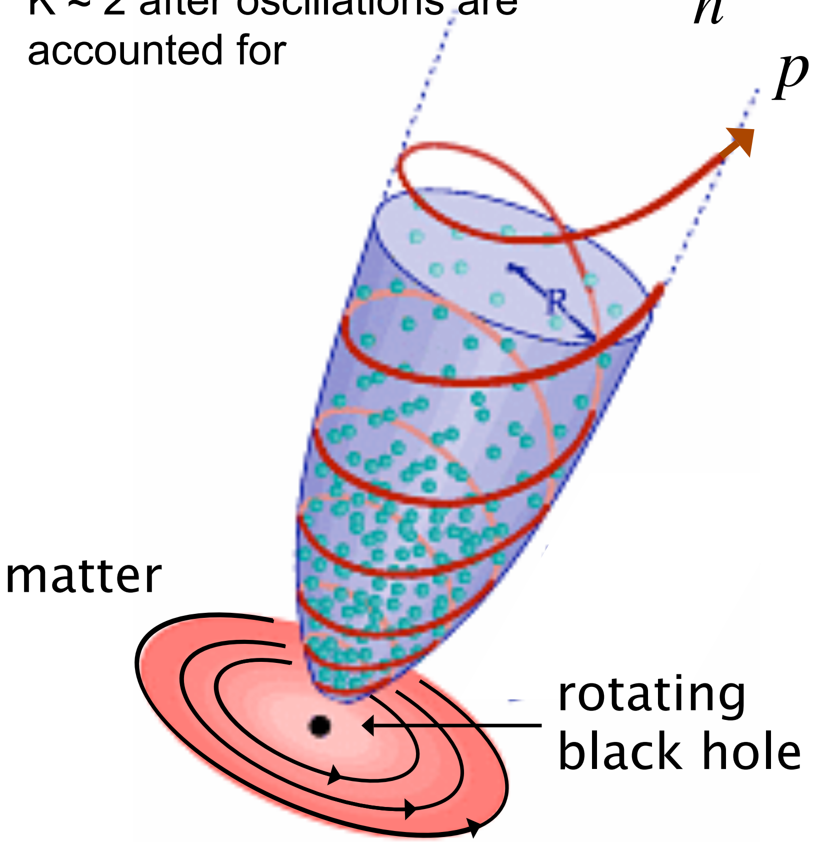
$$1)\ p+\gamma \to \Delta^+ \to p\pi^0 \qquad \text{BR} = 2/3$$

$$2)\ p+\gamma \to \Delta^+ \to n\pi^+ \qquad \text{BR} = 1/3$$

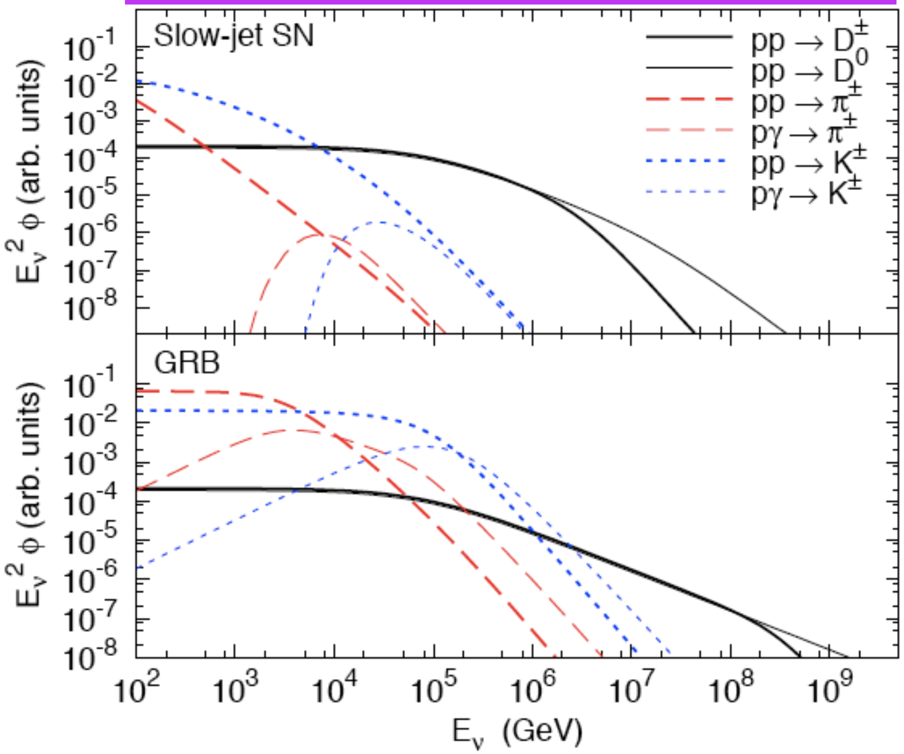
$$\int_{E_{\gamma\,\min}}^{E_{\gamma\,\max}} E_\gamma \frac{dN_\gamma}{dE_\gamma} dE_\gamma = K\int_{E_{\nu\,\min}}^{E_{\nu\,\max}} E_\nu \frac{dN_\nu}{dE_\nu} dE_\nu$$

K ≈ 2 after oscillations are accounted for



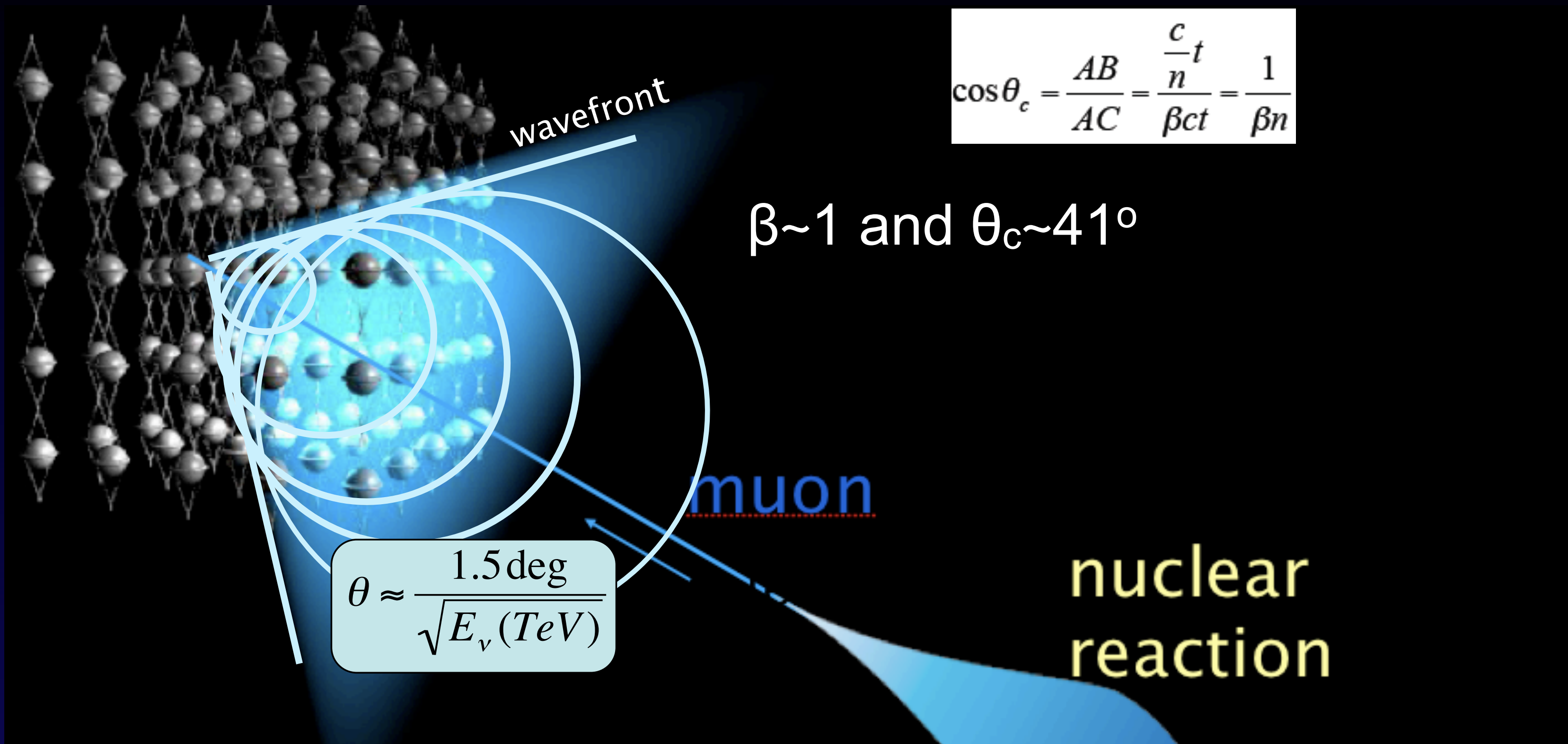


Enberg et al, 2008:
include charm component



Neutrino Telescope Concept Detectors: IceCube and ANTARES Event Topologies

Concept of Neutrino Detector



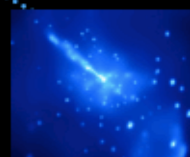
$$\cos\theta_c = \frac{AB}{AC} = \frac{\frac{c}{n}t}{\beta ct} = \frac{1}{\beta n}$$

β~1 and θ_c~41^o

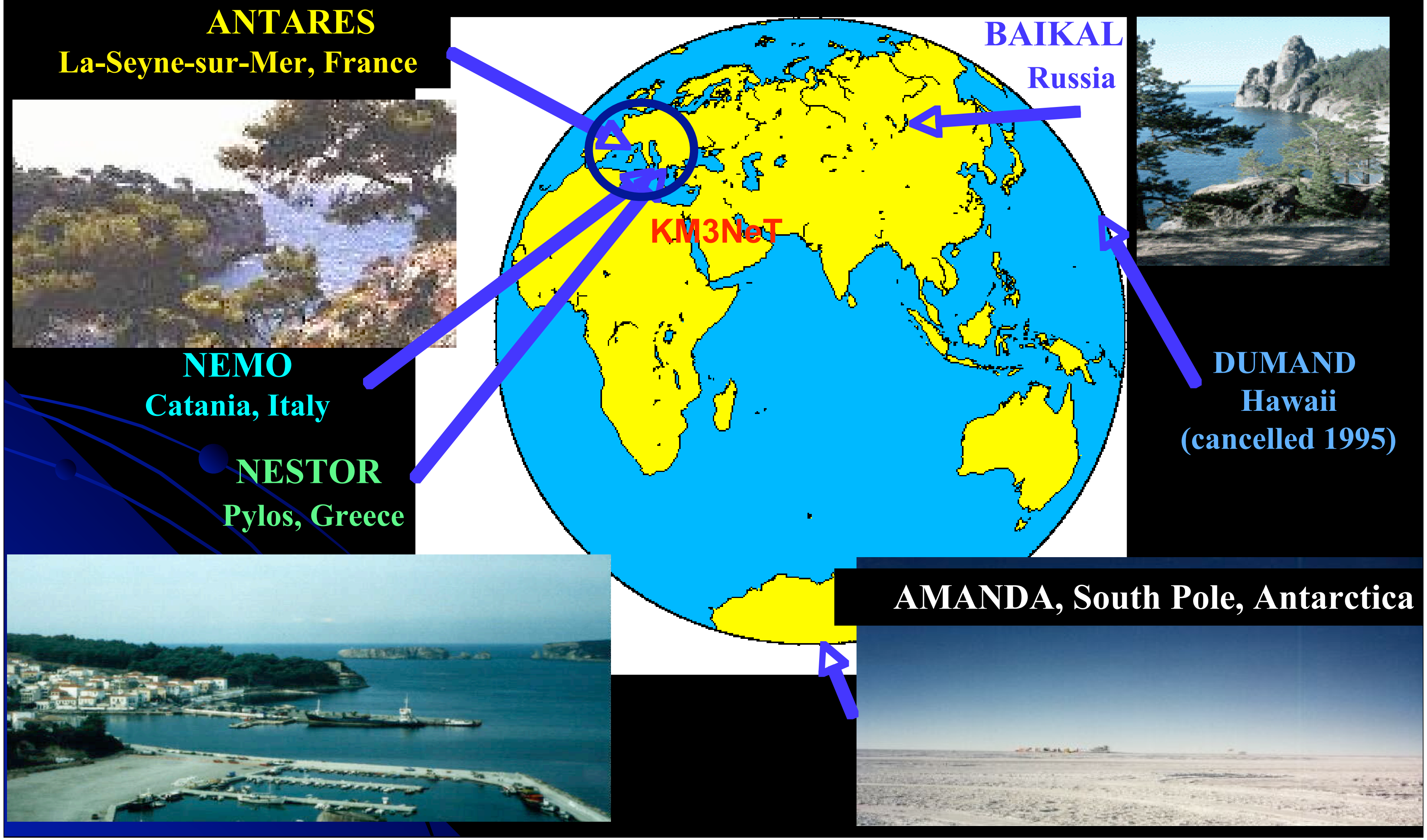
$$\theta \approx \frac{1.5\deg}{\sqrt{E_\nu(TeV)}}$$

Natural radiator is low cost and allows huge instrumented regions but it takes time to know it well! Main systematic error source

Between 300-600 nm about 3.5 x 10^4 Cherenkov photons/m of a muon track

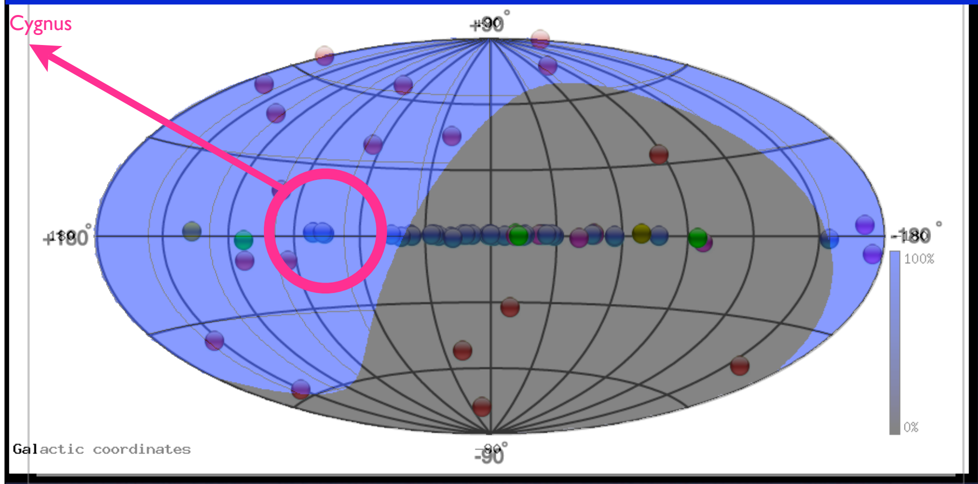


Cherenkov
Neutrino Telescope Projects



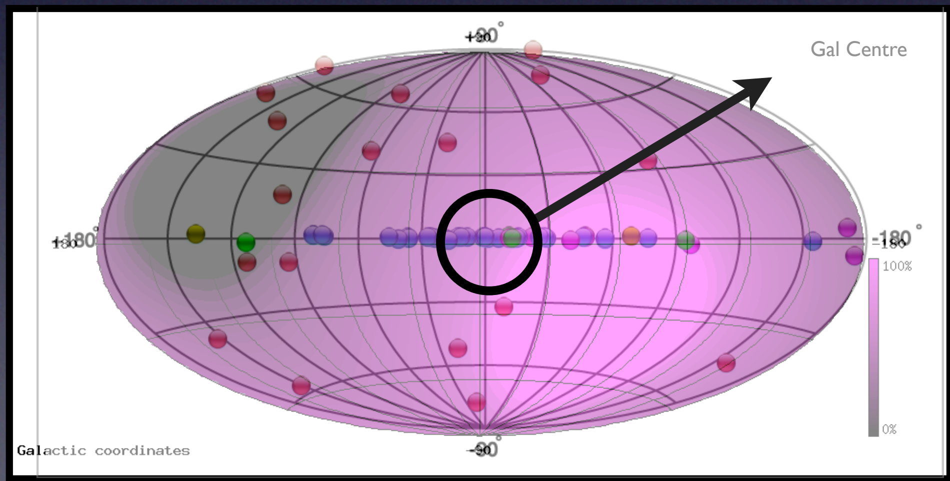
Full Sky Coverage with upgoing neutrinos

To cover better galactic sources we need Med detectors



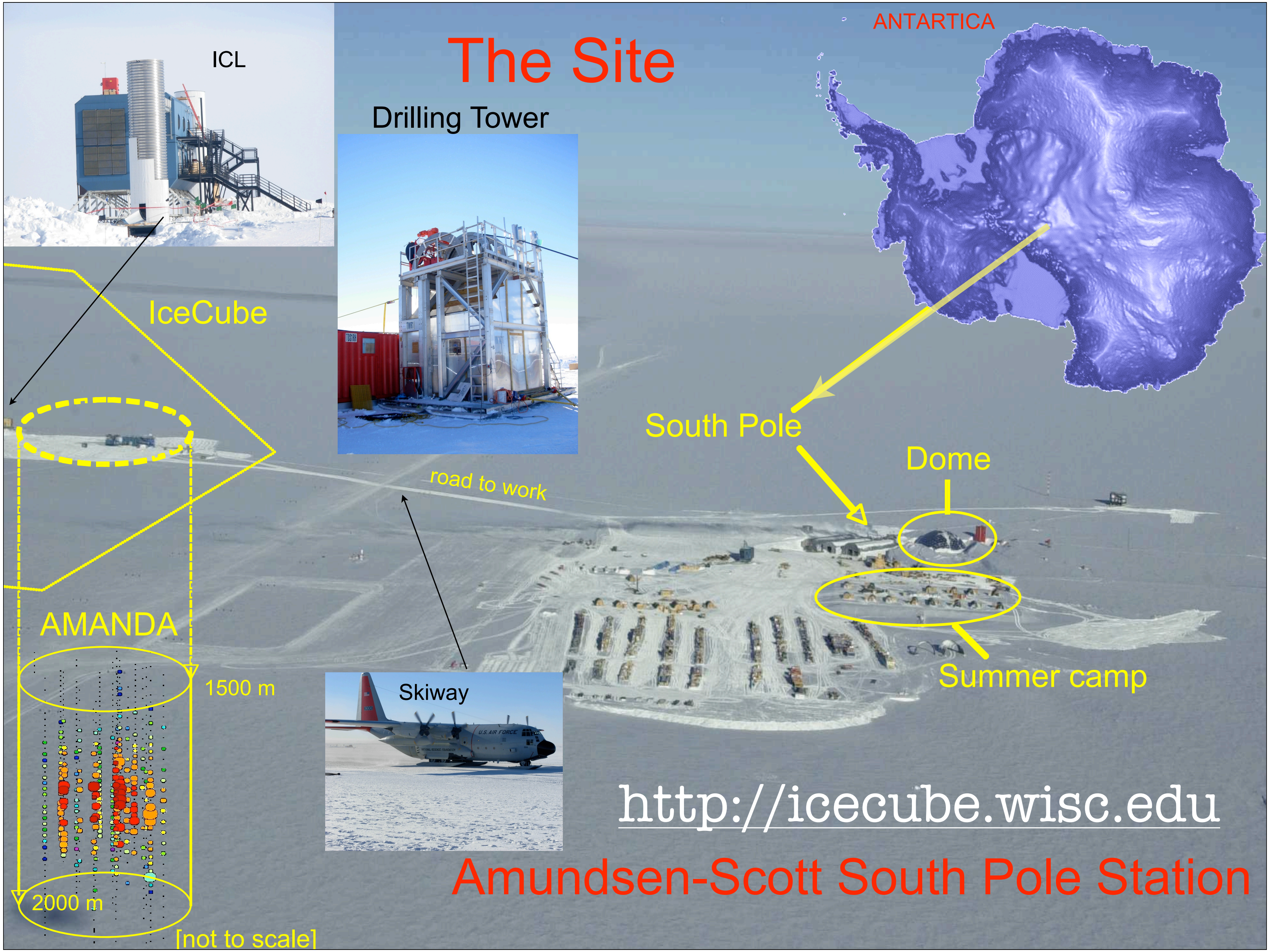
ANTARES 43° N
Galactic Centre 2/3 of day

IceCube/AMANDA at
South Pole

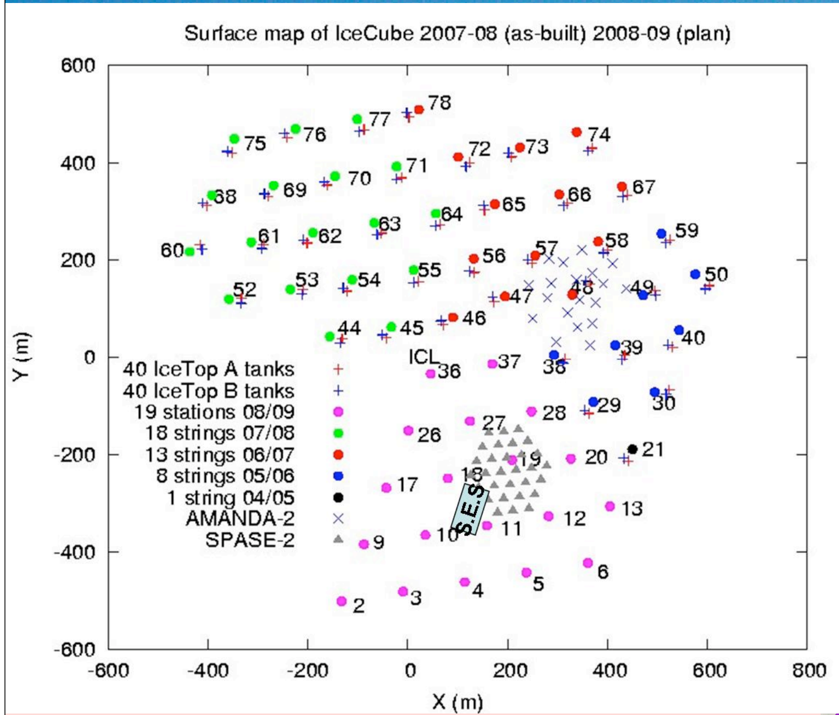


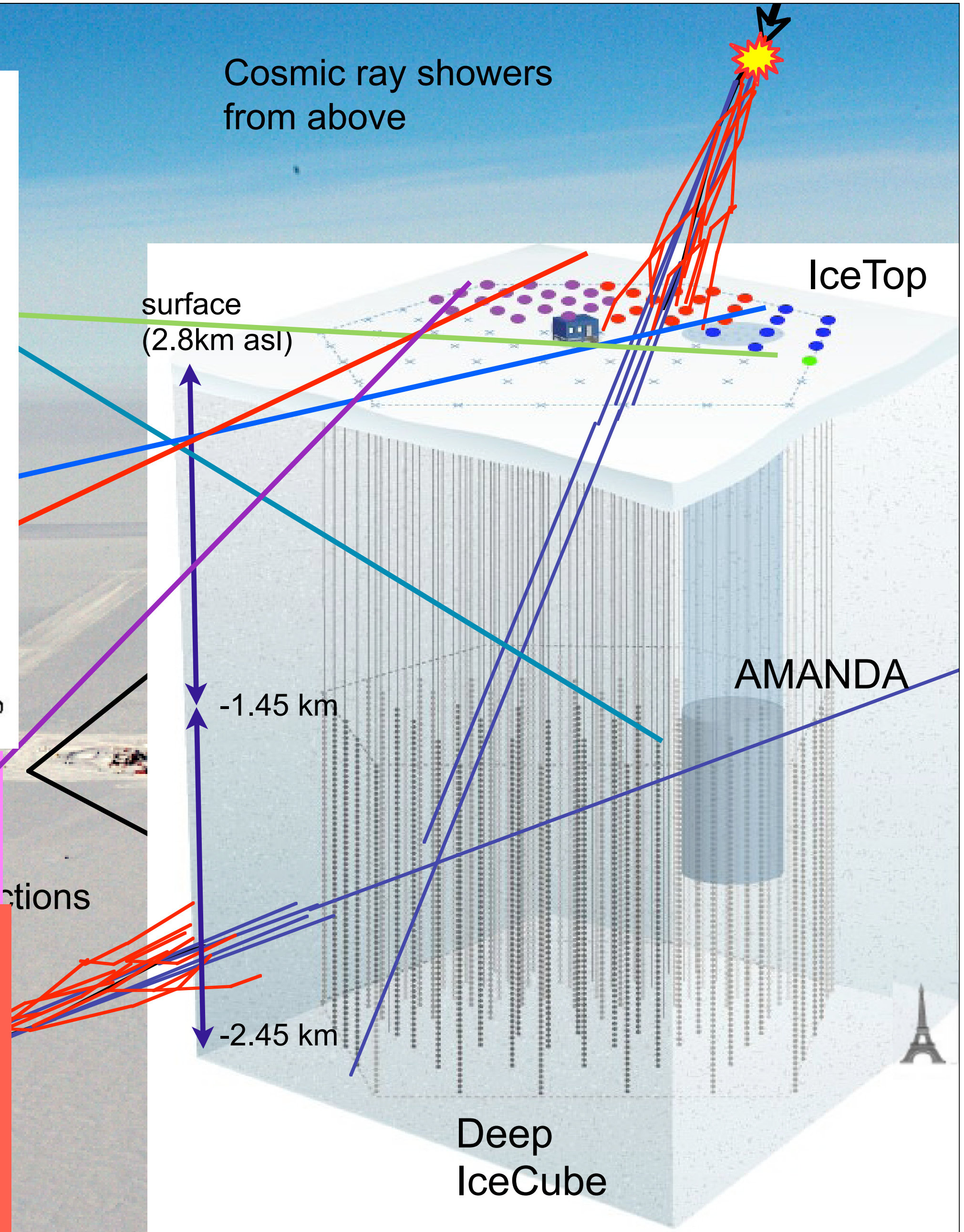
TeV sources from tevcat.uchicago.edu > 70 TeV sources

About 250 physicists, 29 Institutions



The Site
ANTARTICA
ICL
Drilling Tower
IceCube
South Pole
Dome
road to work
AMANDA
1500 m
2000 m
[not to scale]
Skiway
Summer camp
http://icecube.wisc.edu
Amundsen-Scott South Pole Station



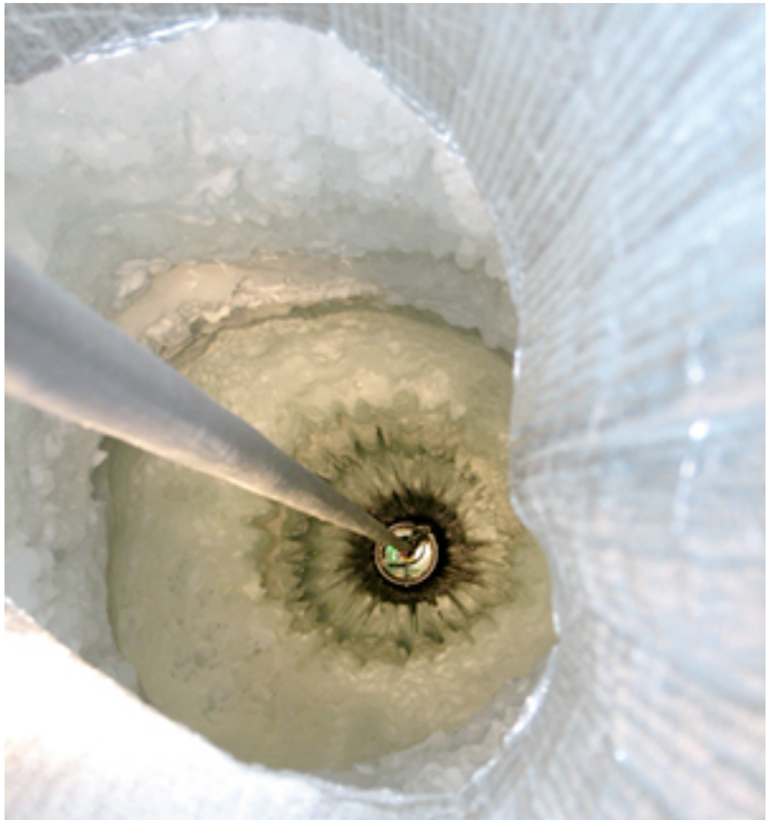


2007-2008: + 18 strings
IC40: 04/08 - 03/09 phys run
IC56: 2008-2009 => IC 56

IC80: 4800 optical modules on 60 strings
17 m between modules
125 m between strings
+ 6 strings for Deep Core
IceTop: 80 stations of 2 tanks with 2 modules

In-ice strings: now 2400 DOMs on 40 strings taking physics data

+ 3 new strings since Dec 6!!!



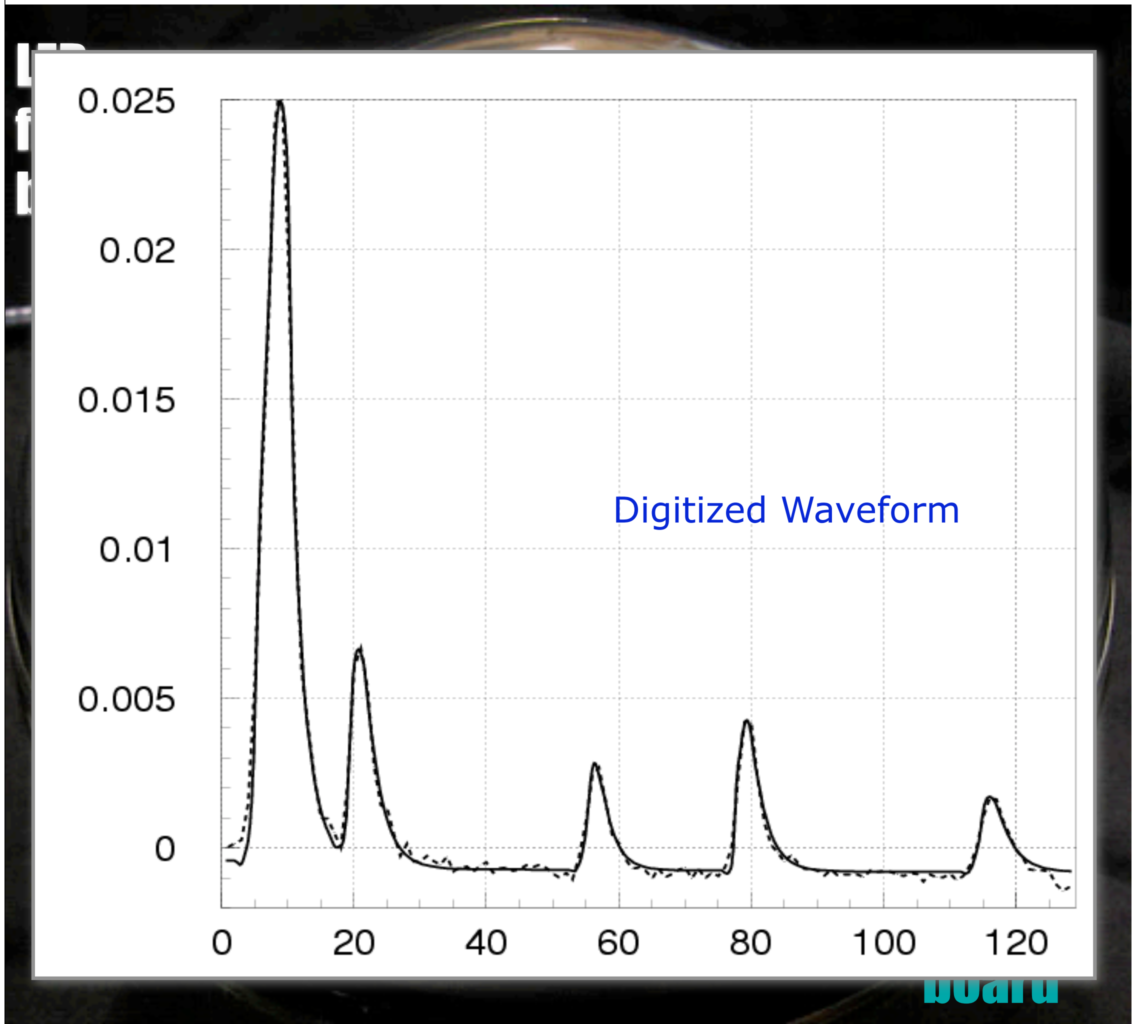
Time for a full hole and start a new one about 2 days: we can deploy 18 strings /season!
About 0.5 TJ in each hole!

Icetop tanks

Two DOMs per tank
Two tanks at the top of each string
Now 80 tanks and 160 DOMs taking physics data

- DOMs with problems ~3%
- Est. survival rate after 15 years: 95%

Digital Optical Module (DOM)



PMT: 10 inch Hamamatsu
Power consumption: 3 W
Digitize at 300 MHz for 400 ns with custom chip
40 MHz for 6.4 μs with fast ADC
Dynamic range 200pe/15 nsec

Send all data to surface over copper
2 sensors/twisted pair.
Flasherboard with 12 LEDs
Local HV

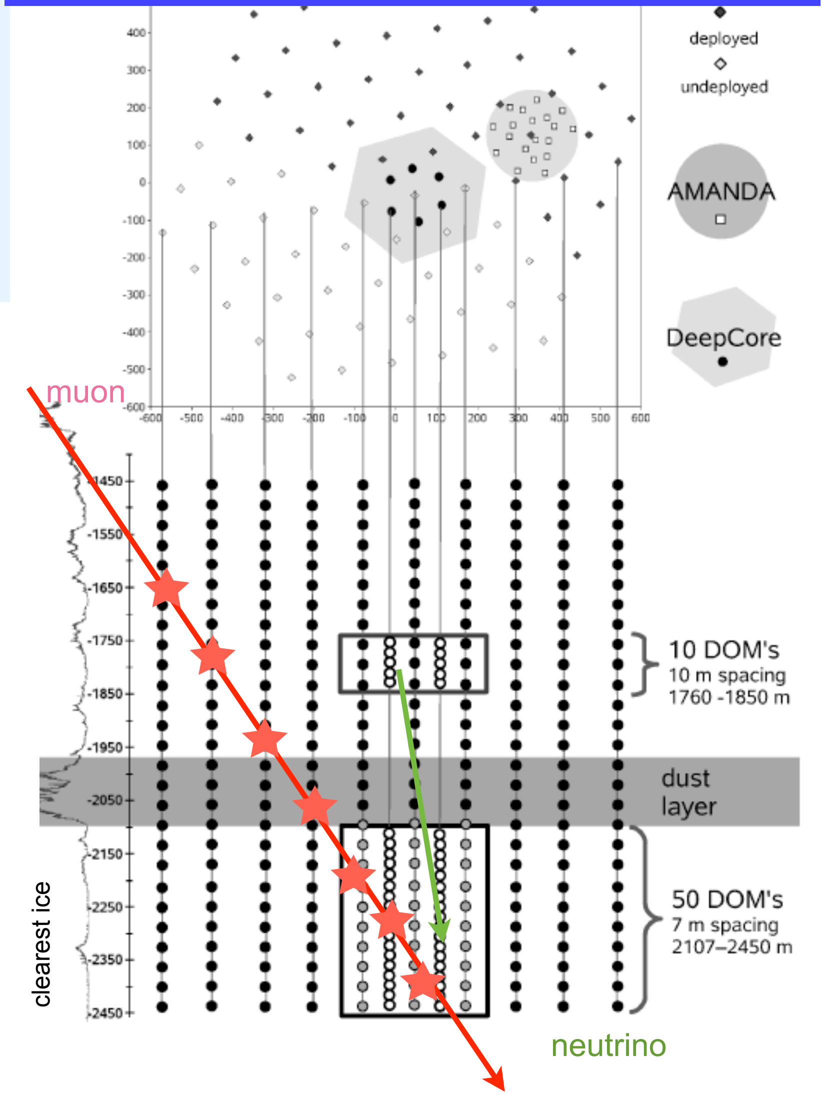
Clock stability: $10^{-10} \approx 0.1$ nsec / sec
Synchronized to GPS time every ≈10 sec
Time calibration resolution = 2 nsec

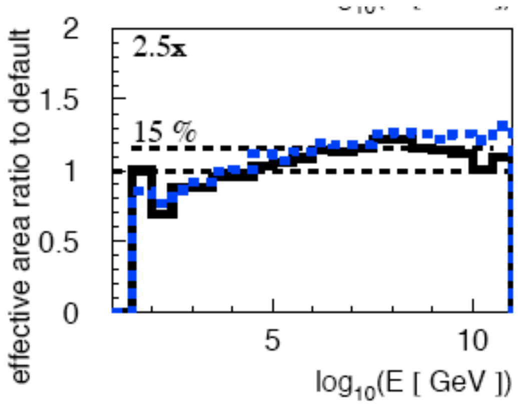
Daq paper: **arXiv:0810.4930**

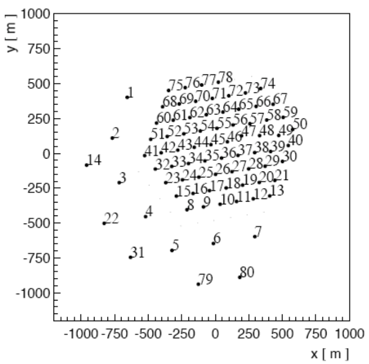
Plans for Future Seasons

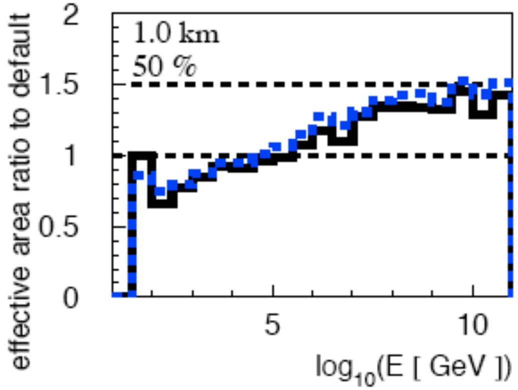
- 08/09 season (just started!): 16-19 more strings and 19 IceTop stations, 1st deep core string with high QE PMTs (20%->40%)
- IC56 science run start in April 09
- 09/10 season: add 15+5 deep core strings
- 10/11 complete IceCube construction
- HE extension: up to 50% gain at >PeV energies with largely spaced 12 outer strings

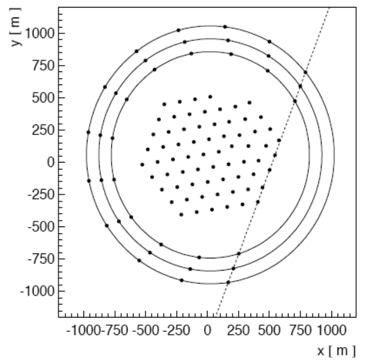
Deep core uses IceCube as a VETO to identify low energy and downgoing νs



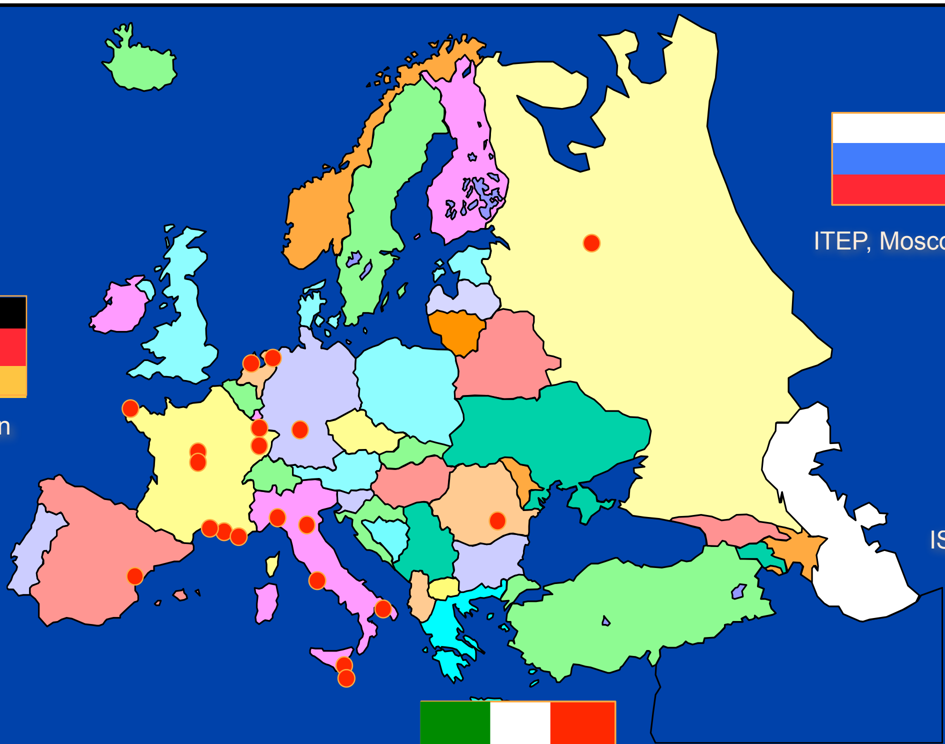








The ANTARES Collaboration



NIKHEF, Amsterdam
KVI Groningen
NIOZ Texel

University of Erlangen

IFIC, Valencia
UPV, Valencia

CPPM, Marseille
DSM/IRFU/CEA, Saclay
APC Paris
IPHC (IReS), Strasbourg
Univ. de H.-A., Mulhouse
IFREMER, Toulon/Brest
C.O.M. Marseille
LAM, Marseille
GeoAzur Villefranche

ITEP, Moscow

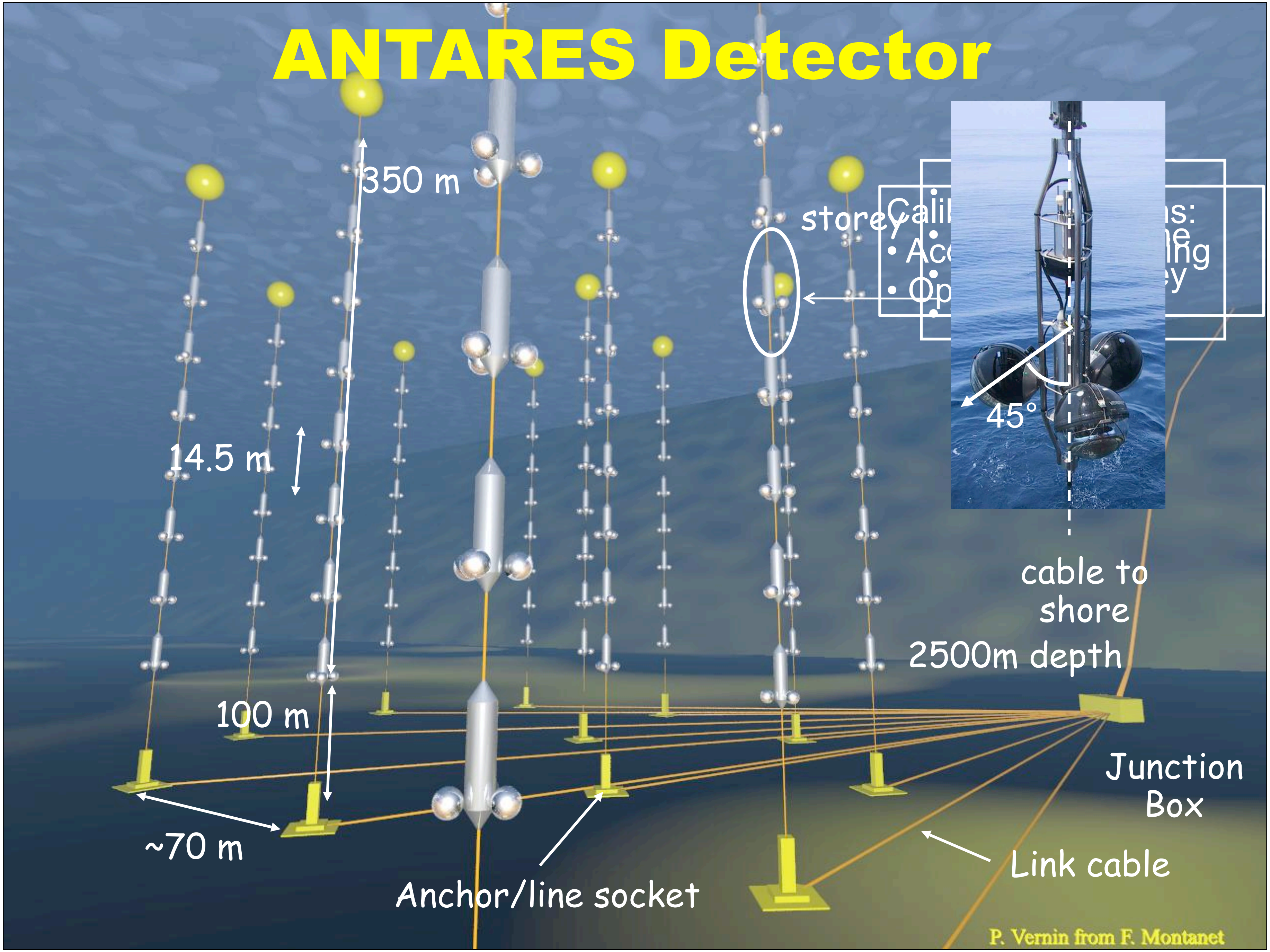
ISS, Bucharest

University/INFN of Bari
University/INFN of Bologna
University/INFN of Catania
LNS – Catania
University/INFN of Pisa
University/INFN of Rome
University/INFN of Genova

7 European countries
24 Institutions

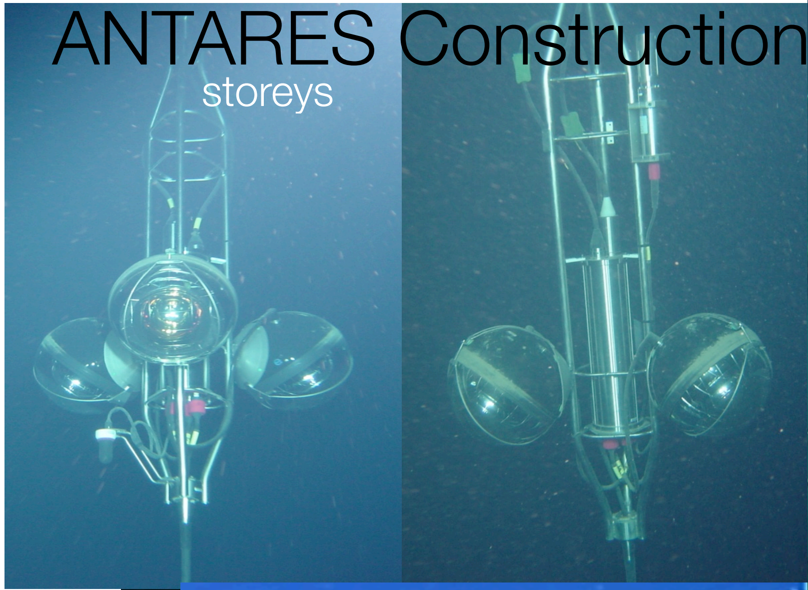
The first undersea neutrino telescope is complete since May 08

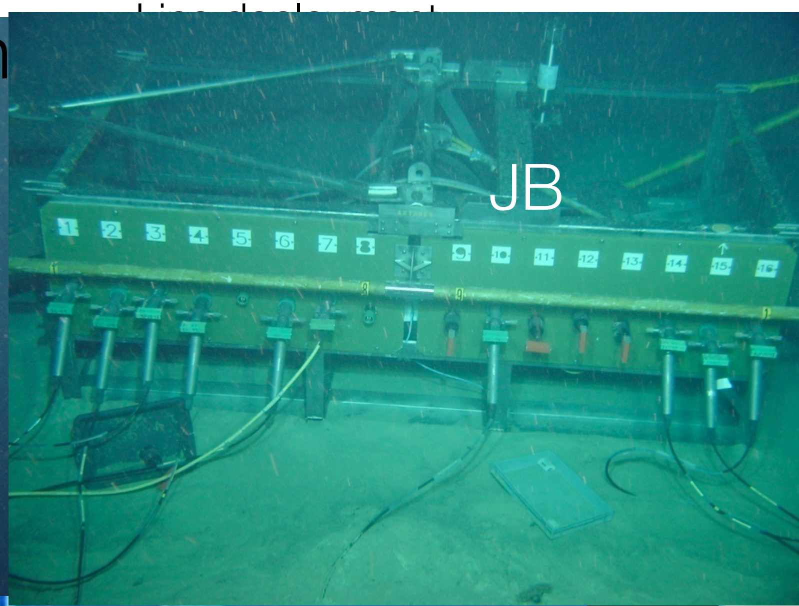
ANTARES Detector

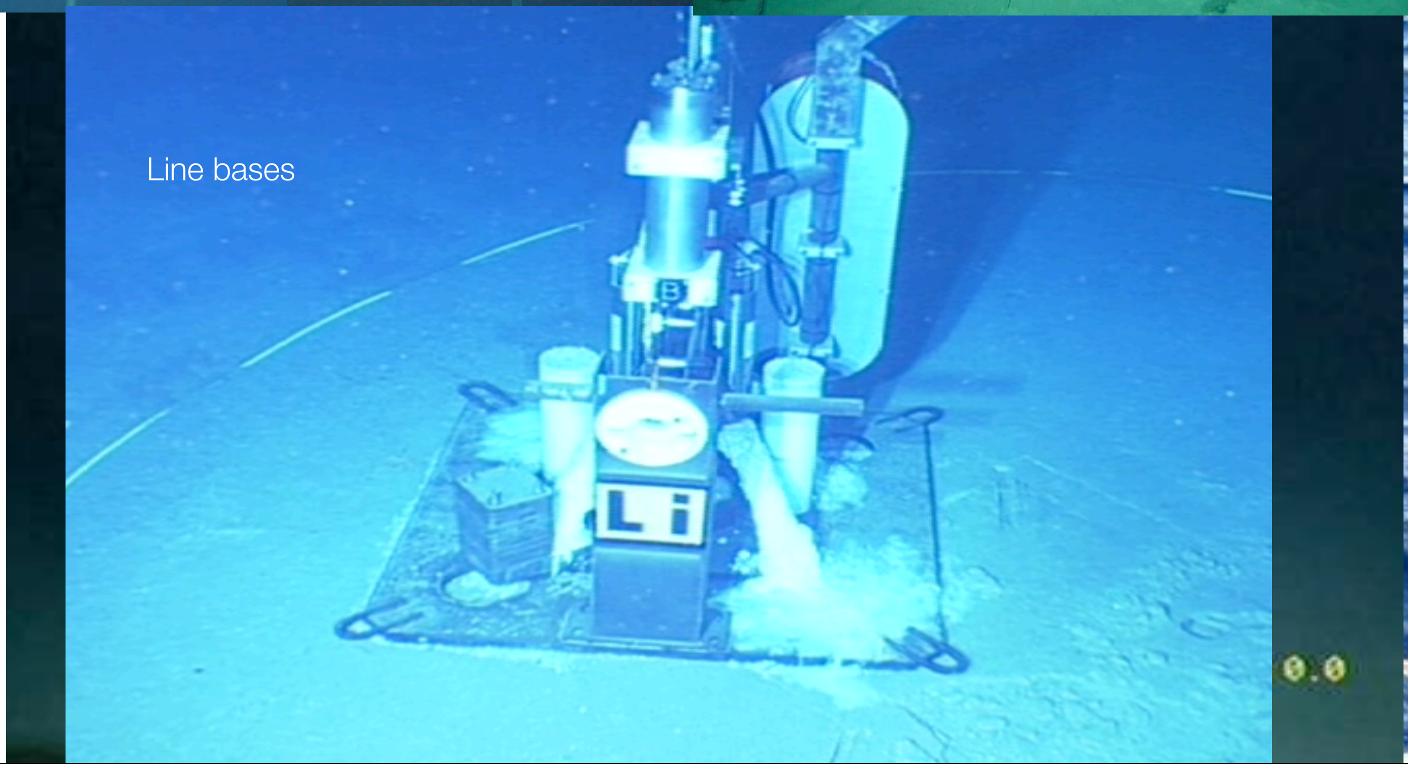


The ANTARES Site and Control Room

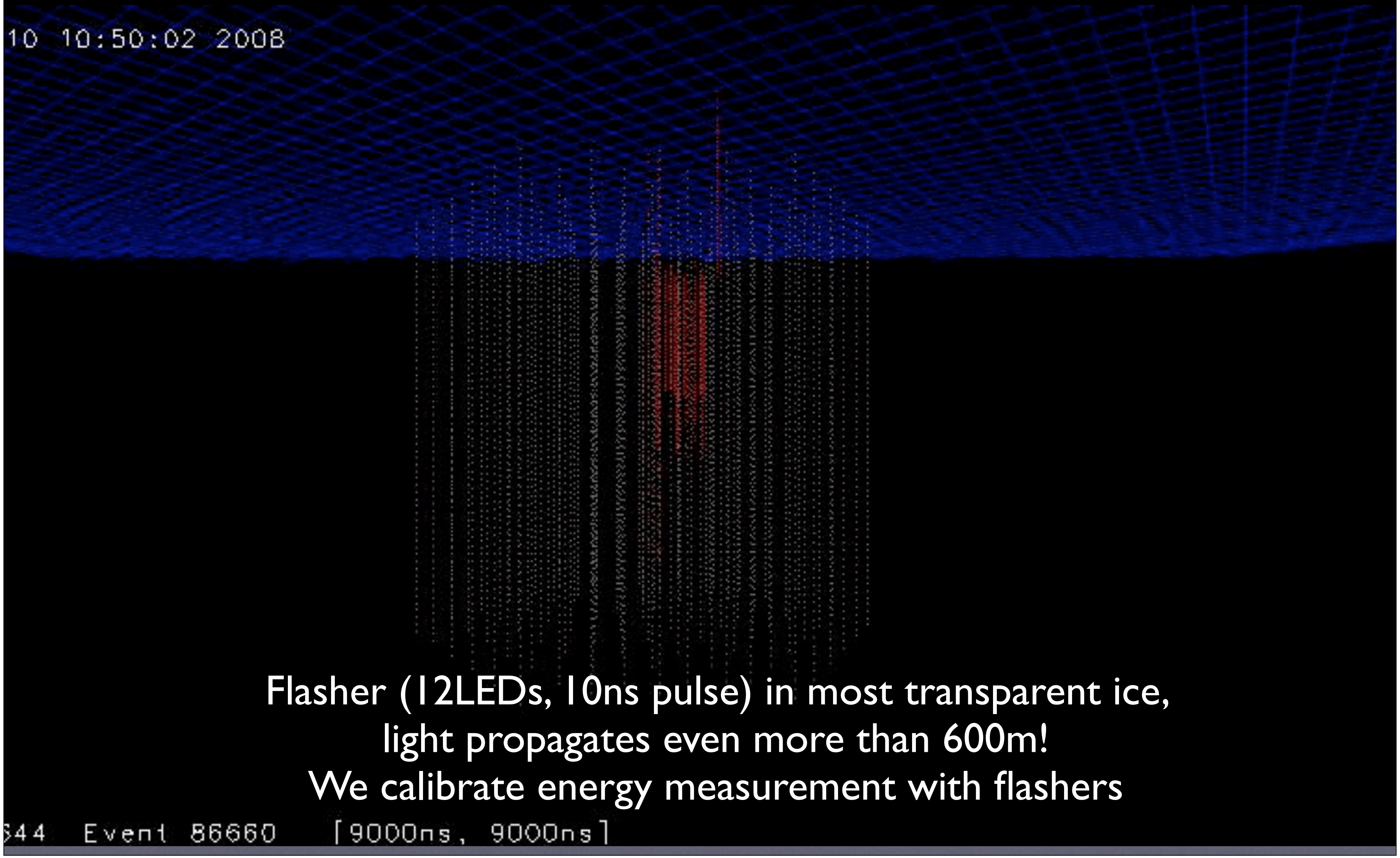
ANTARES Construction



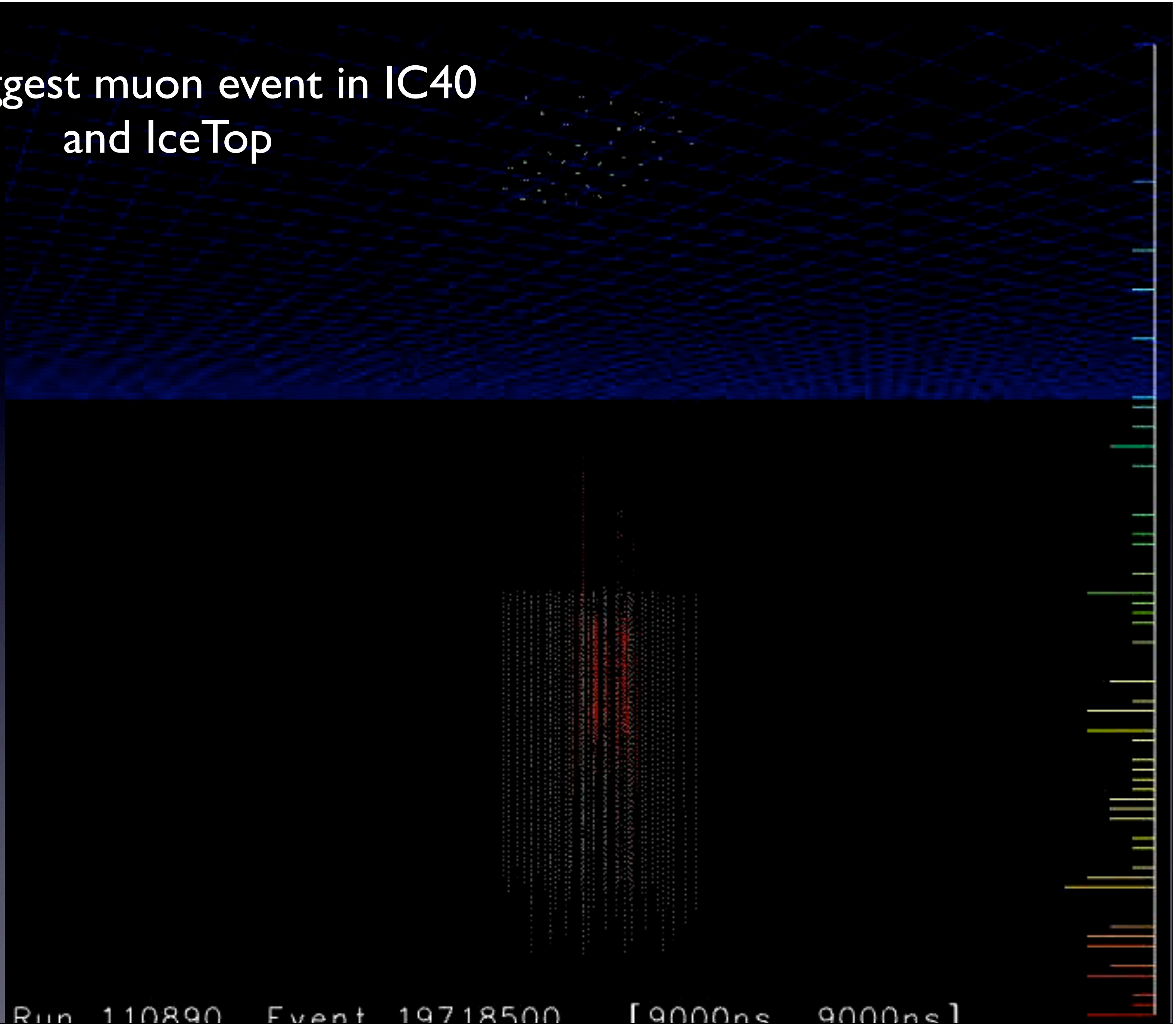




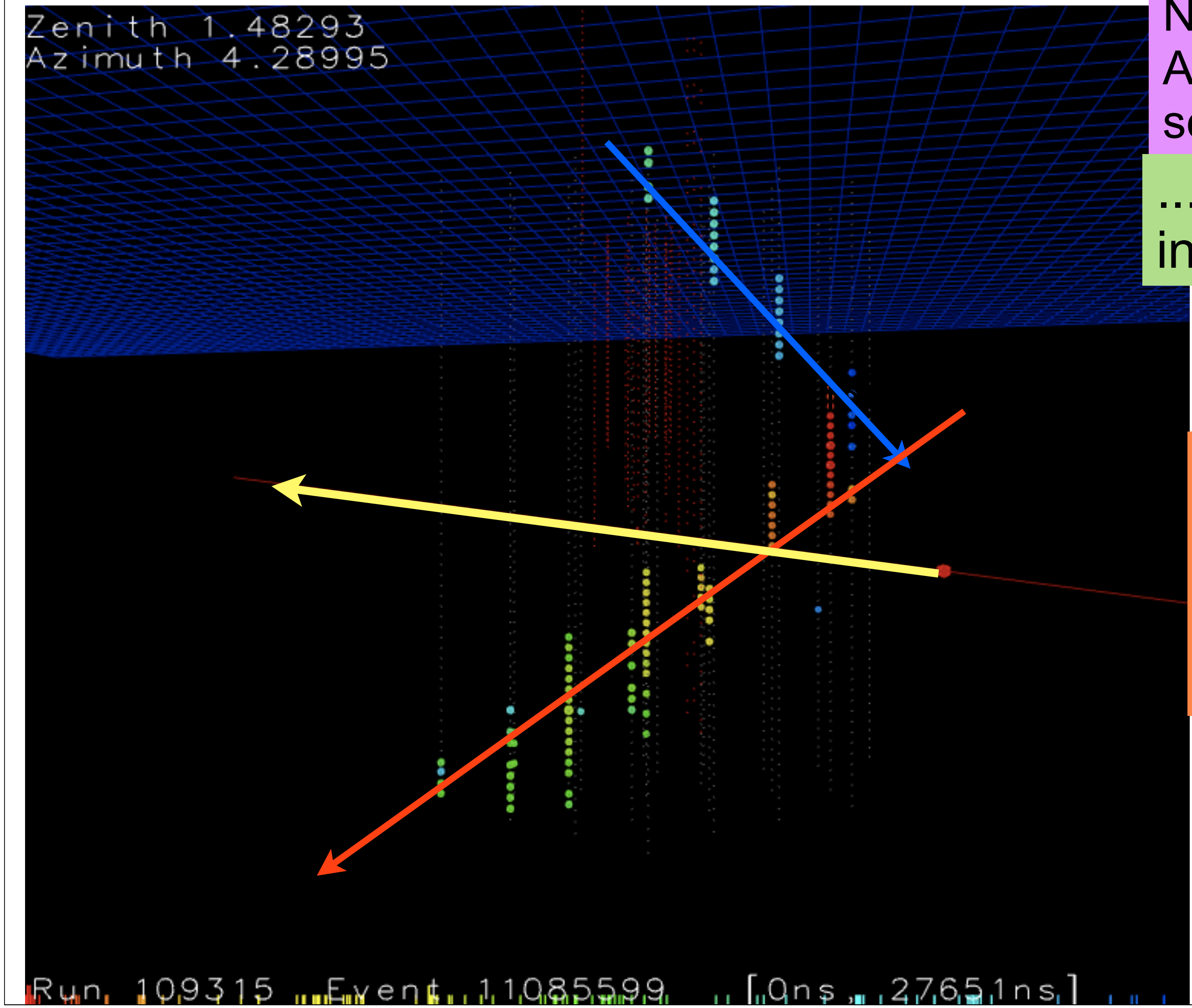
A flasher cascade-like event and muon in IC40



The biggest muon event in IC40 and IceTop



Coincident muons



New events respect to AMANDA/ANTARES scale detectors!

...but also an insidious background

Solution: use preselection of hits (topological trigger)

Natural radiators: deep ice and sea water

We need transparent and dark media and deep detectors
Use Earth as a filter to detect neutrinos

Getting to know the medium...

Light propagating in a medium is absorbed and scattered.

$$I = I_0 \frac{A}{4\pi R^2} e^{-R/\lambda_{att}^{eff}}$$

$$\frac{1}{\lambda_{att}} = \frac{1}{\lambda_{abs}} + \frac{1}{\lambda_{scatt}}$$

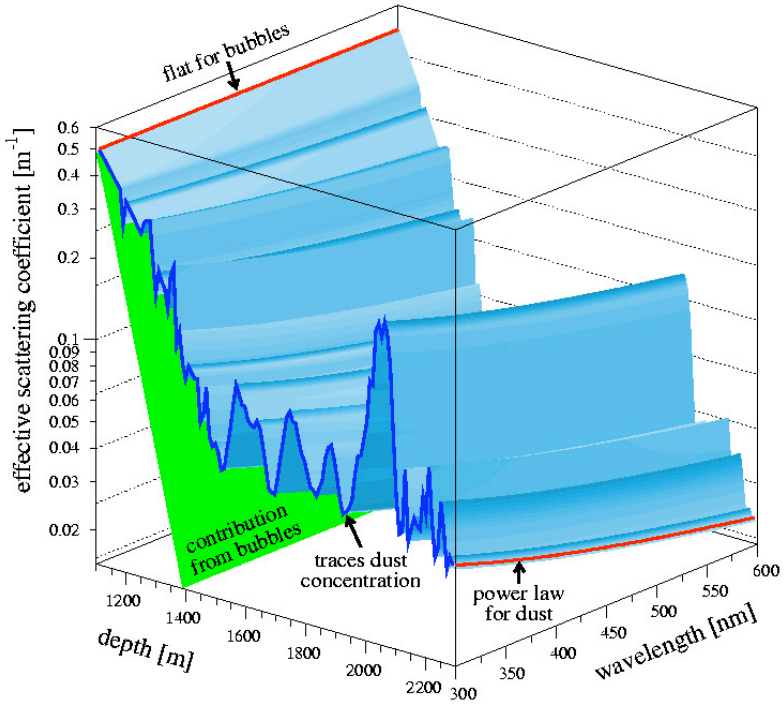
$$\lambda_{sct}^{eff} \simeq \frac{\lambda_{sct}}{1 - \langle \cos\theta \rangle}$$

Scattering is the main factor limiting the angular resolution together with PMT TTS and electronics resolution.

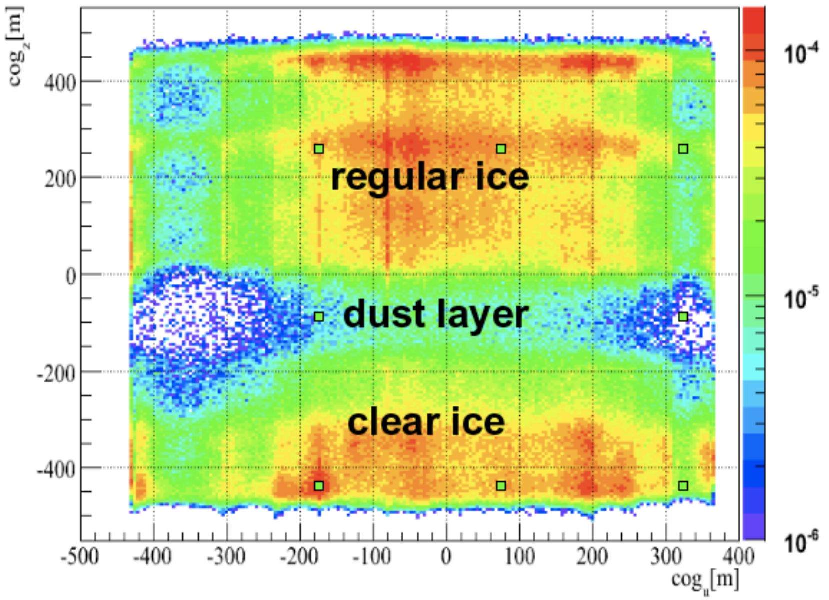
Sea water: λ_{att} ~ 50 m λ_{abs} ~ 50-60 m λ^{eff}_{scatt} > 200 m @ 450 nm

Polar ice: λ_{abs} ~ 110 m λ^{eff}_{scat} ~ 20 m @ 400 nm

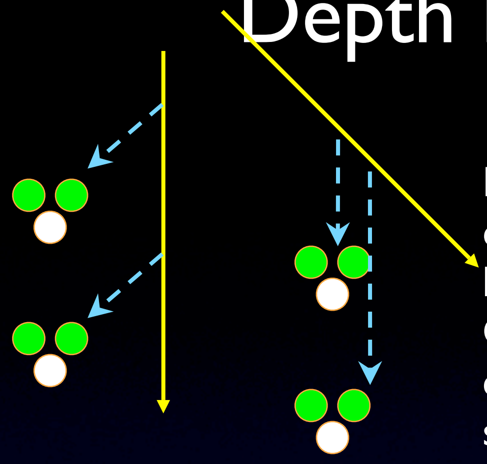
Ice scattering and absorption is depth dependent



Muon 'radiography' of ice

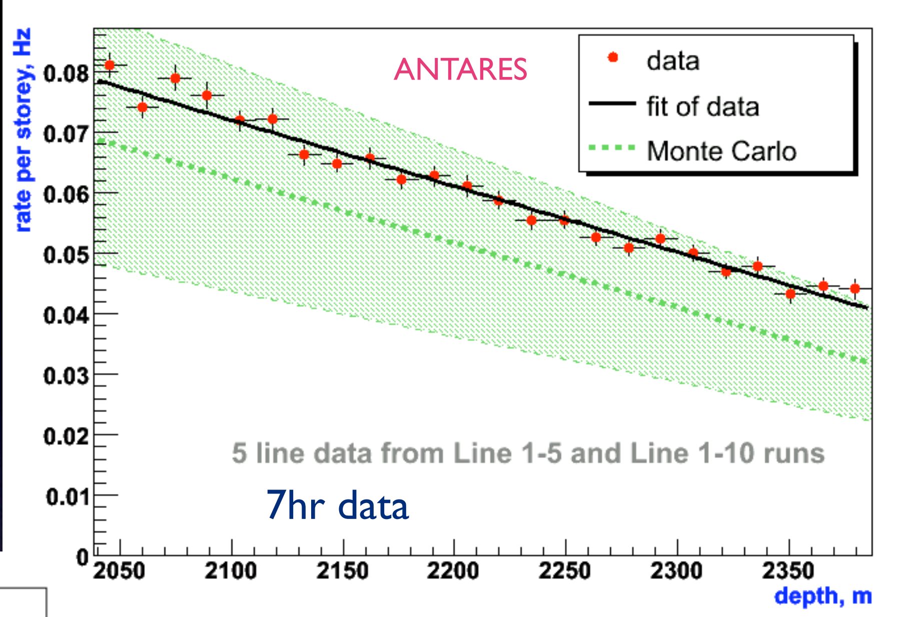


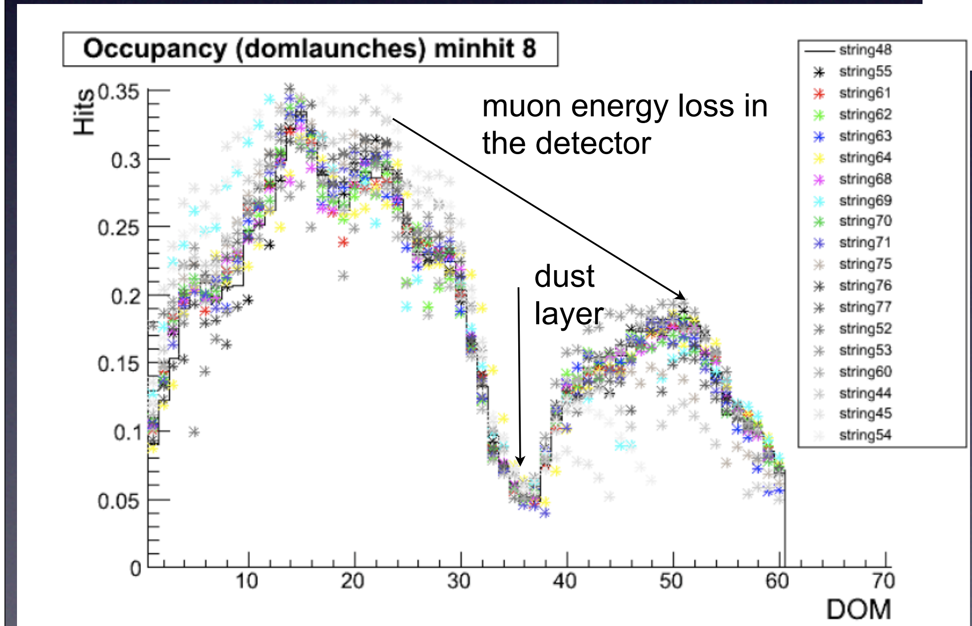
Depth Dependency and light scattering



Flux reduction vs energy due to energy loss of muons. Obtained after correcting for OM sensitivity coefficients calculated from ^{40}K rates.

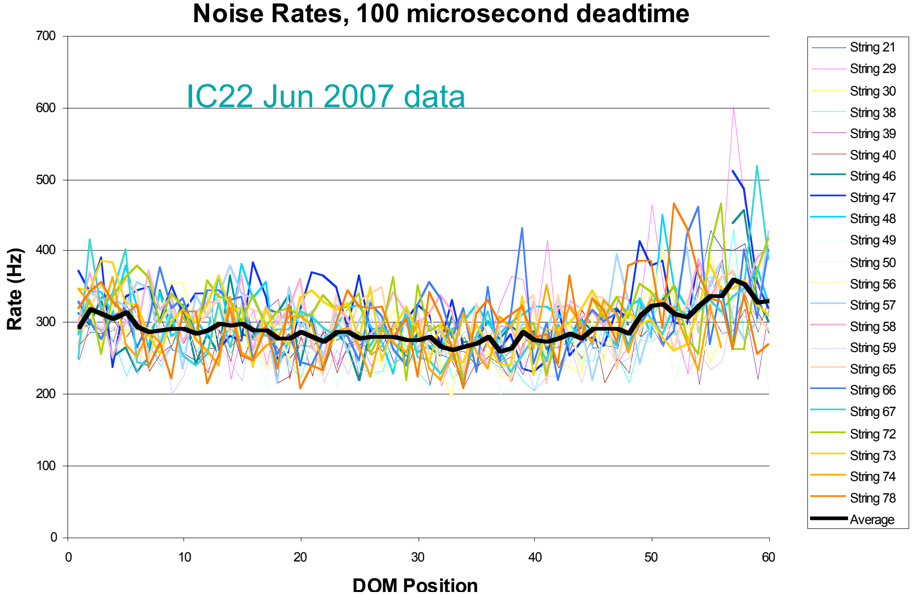
Data/MC ratio ≈ 1.13

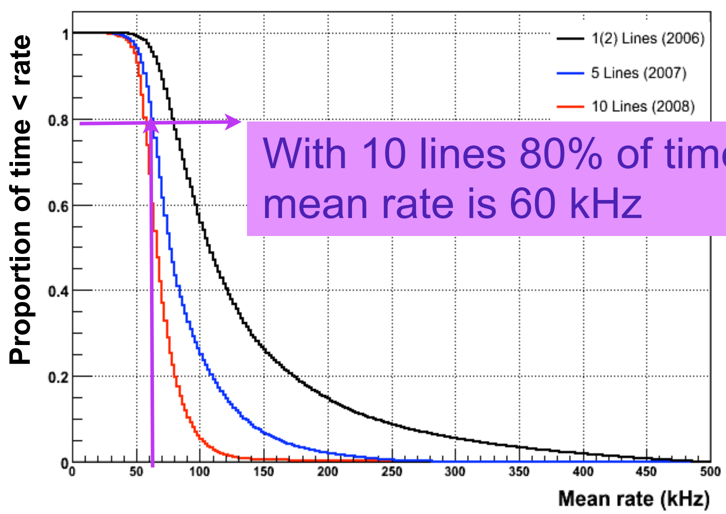




IceCube: Main uncertainty in ice due to depth dependence of ice absorption and scattering

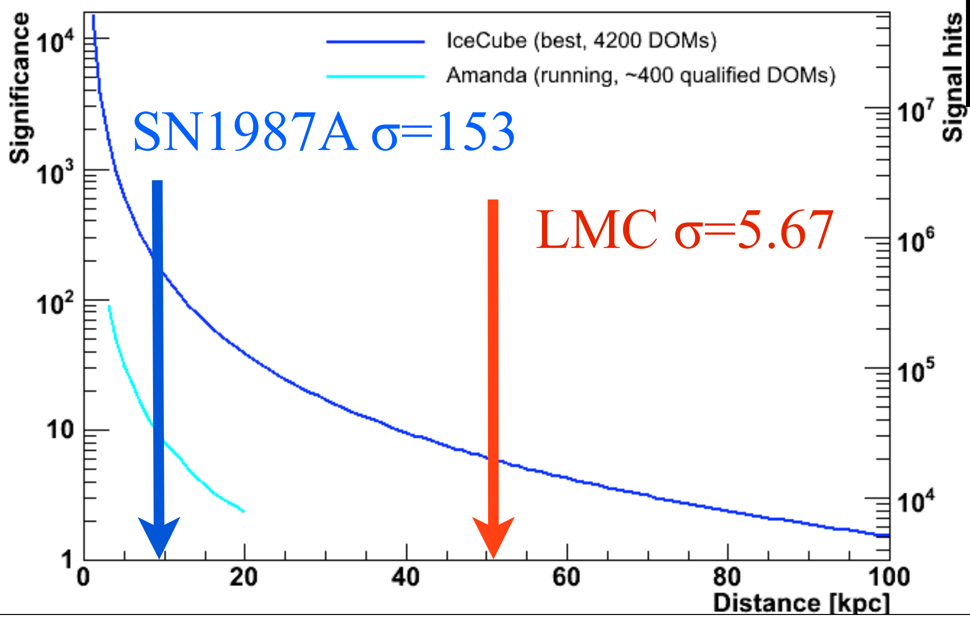
Optical Noise in the sea and ice





With 10 lines 80% of time mean rate is 60 kHz

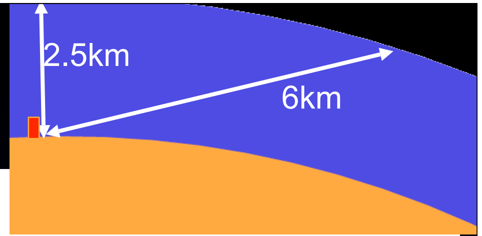
Significance (for 10s)

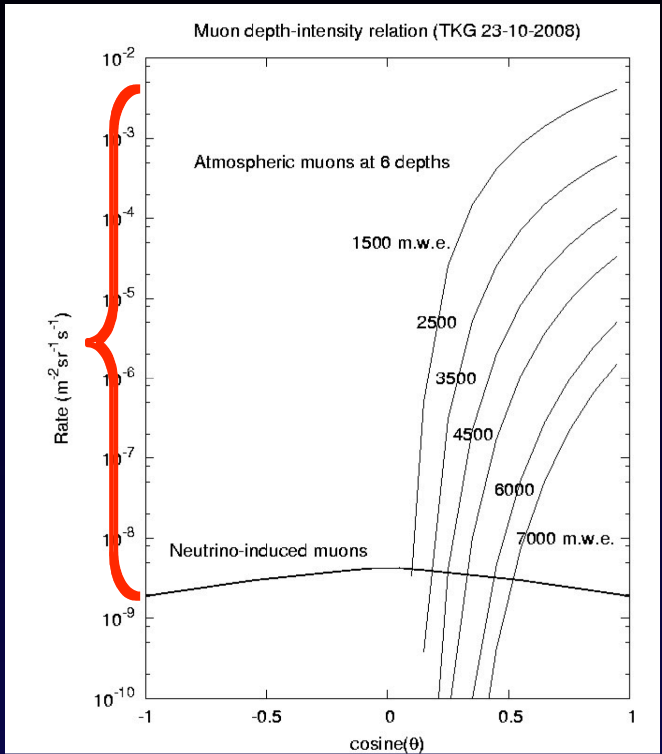


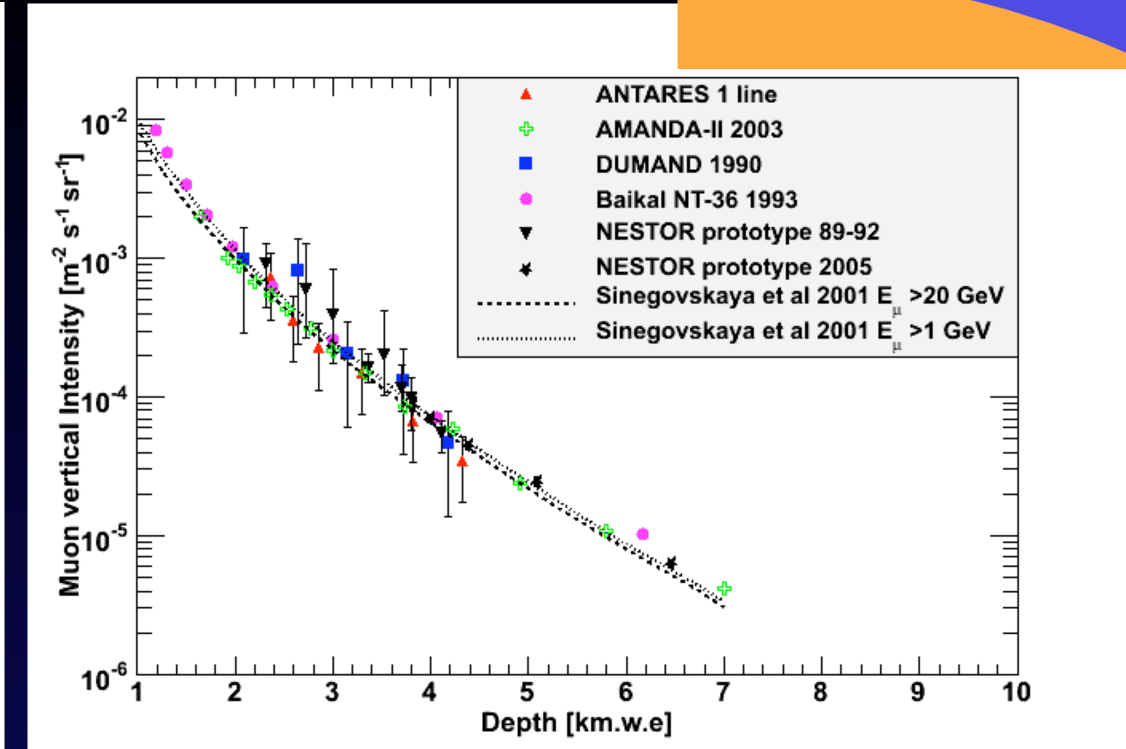
Strong correlation between burst rate and current
Seasonal dependent

Ice is a quiet medium: SN collapse search is possible!

Deep detectors

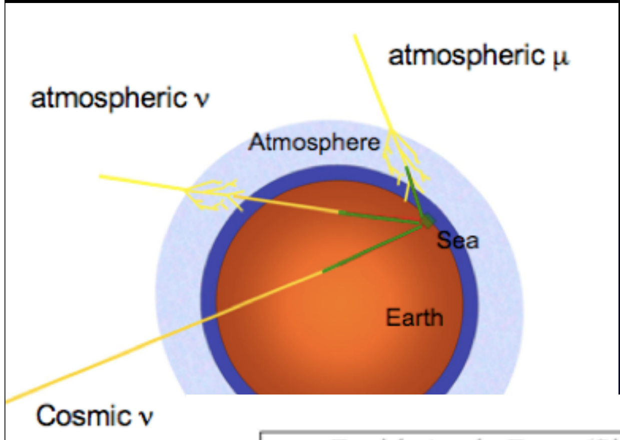




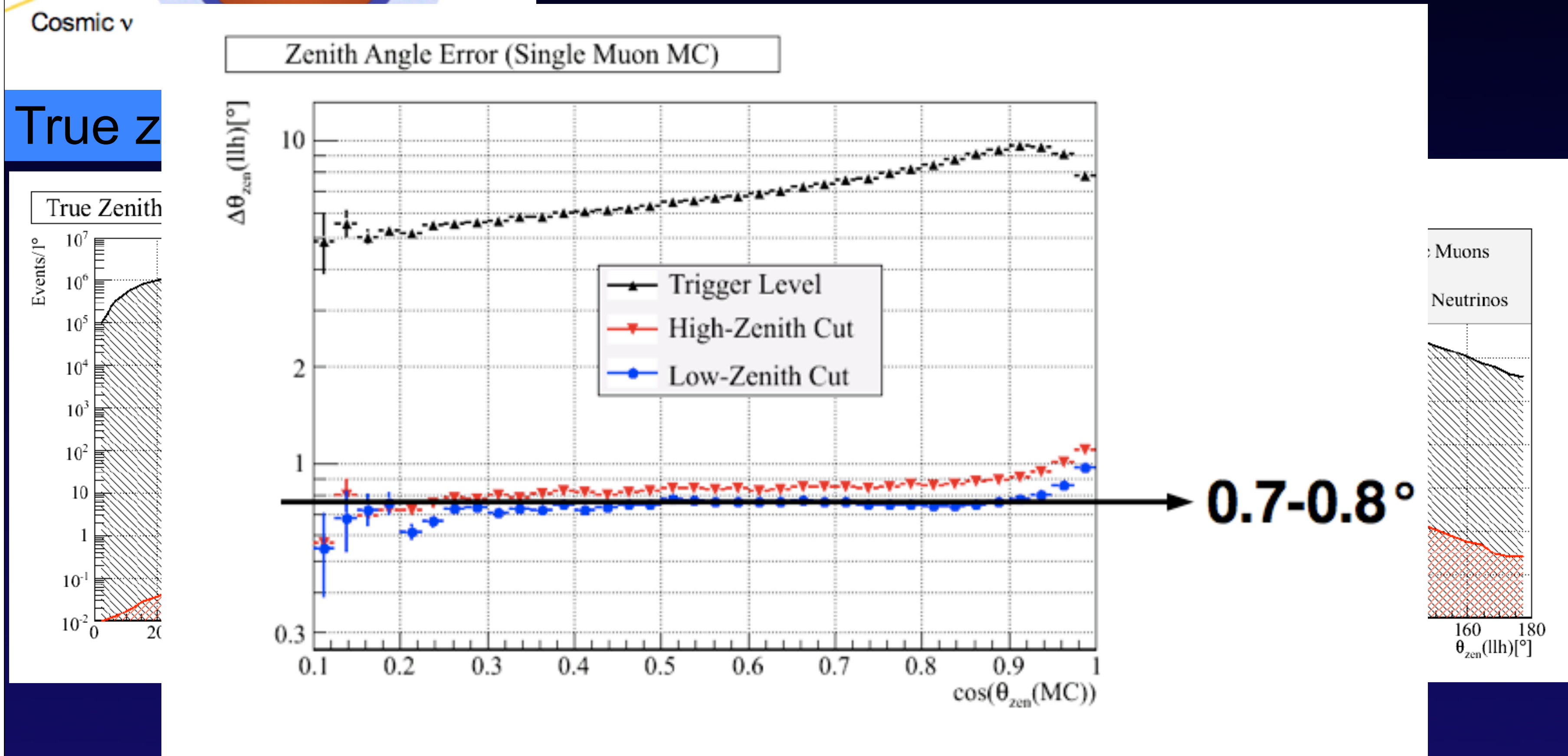


Million to 1 background to signal from above.
→ Use Earth as filter; look for neurtinos from below.

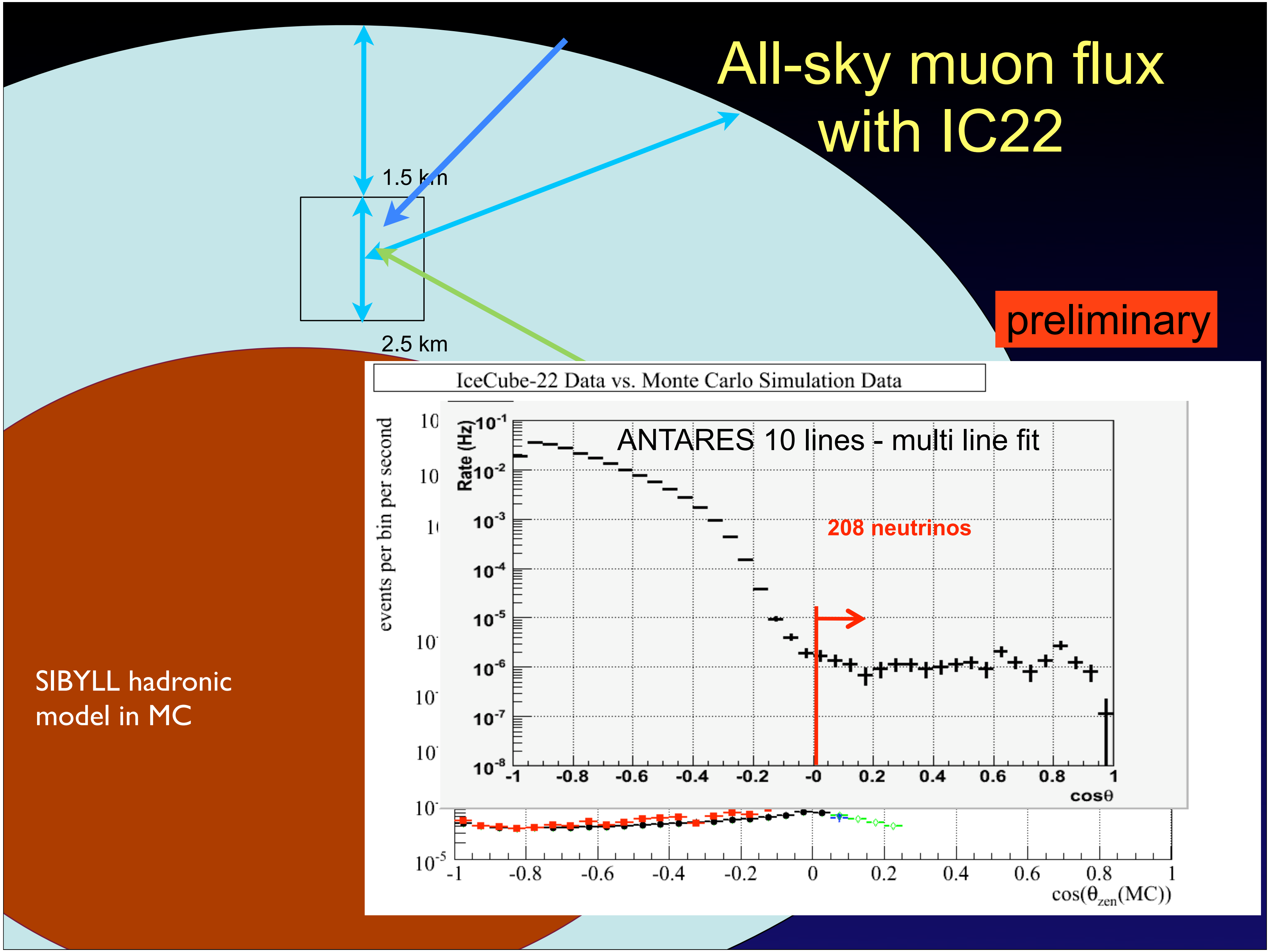
Reconstruction



Quality cuts required to remove atmospheric muon background

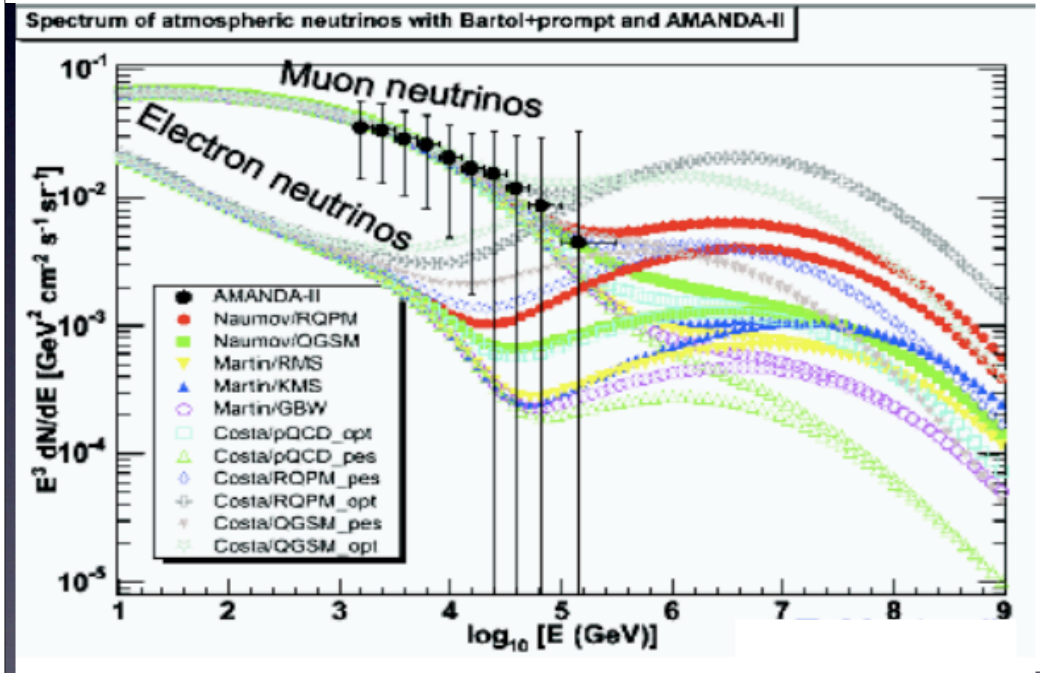


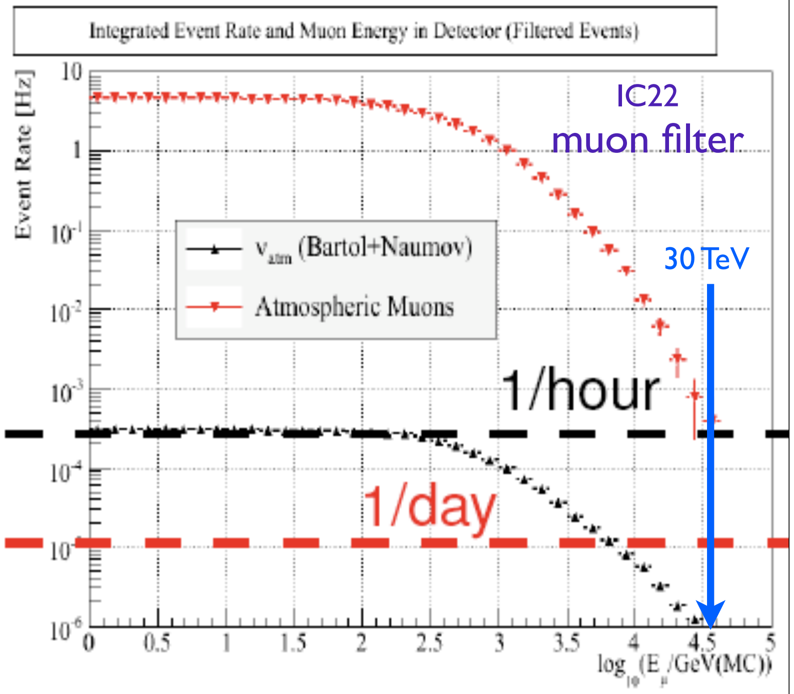
All-sky muon flux with IC22



Atmospheric neutrinos and muons: charm component

Detector config	Phys run	Trigger rate	(8DOMs in 5 usec)
IC9	137d	80 Hz	
IC22	290d	670 Hz	
IC40	May 08-Apr 09	1.1 kHz	



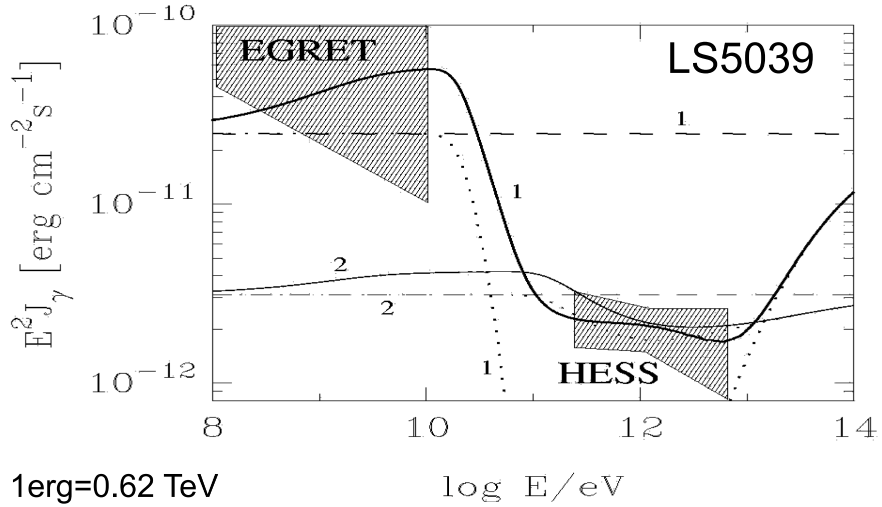


First measurement above 50 GeV of nue atmospheric neutrinos possible: 1500 events/200 d
IceCube has access to prompt muon and neutrino region!


SS433 VLA
GRS 1915+105 VLA
Geminga XMM-Newton
M87 Hubble
NGC 4261 Hubble
Looking for
Hadronic Point-sources
Vela Pulsar Fermi Gamma Ray Space Telescope
Cas A Hubble
Crab Hubble

Example of fluxes for discovery

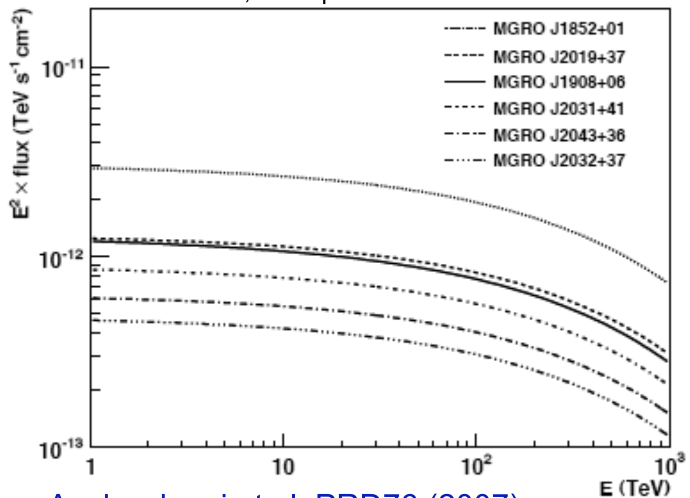
Aharonian, Anchordoqui, Khangulyan, TM, astro-ph/0508658



1erg=0.62 TeV

Milagro sources: 9 in the galactic plane

Halzen et al, astro-ph/0803.0314



Anchordoqui et al, PRD76 (2007)
MGRO 2019+37 with $E^{-2.4}$ and Milagro flux at 20TeV 5σ in 2 yrs for IceCube

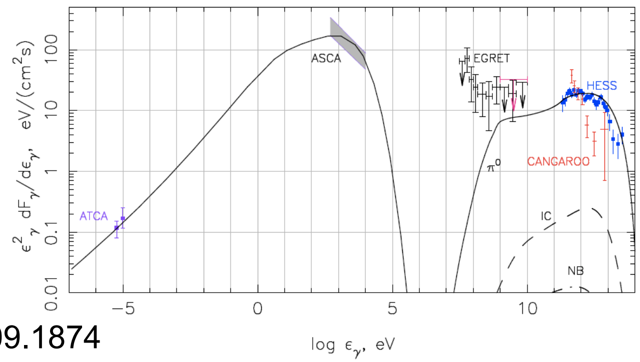
10^{-12}-10^{-11} E^{-2} TeV^{-1} cm^{-2} s^{-1}

a SNR at d = 1 kpc transfers W = 10^{50} erg
to cosmic rays interacting with molecular clouds
with density n = 1 cm^{-3}

$$E\frac{dN_\gamma}{dE}(>1\,TeV) =$$

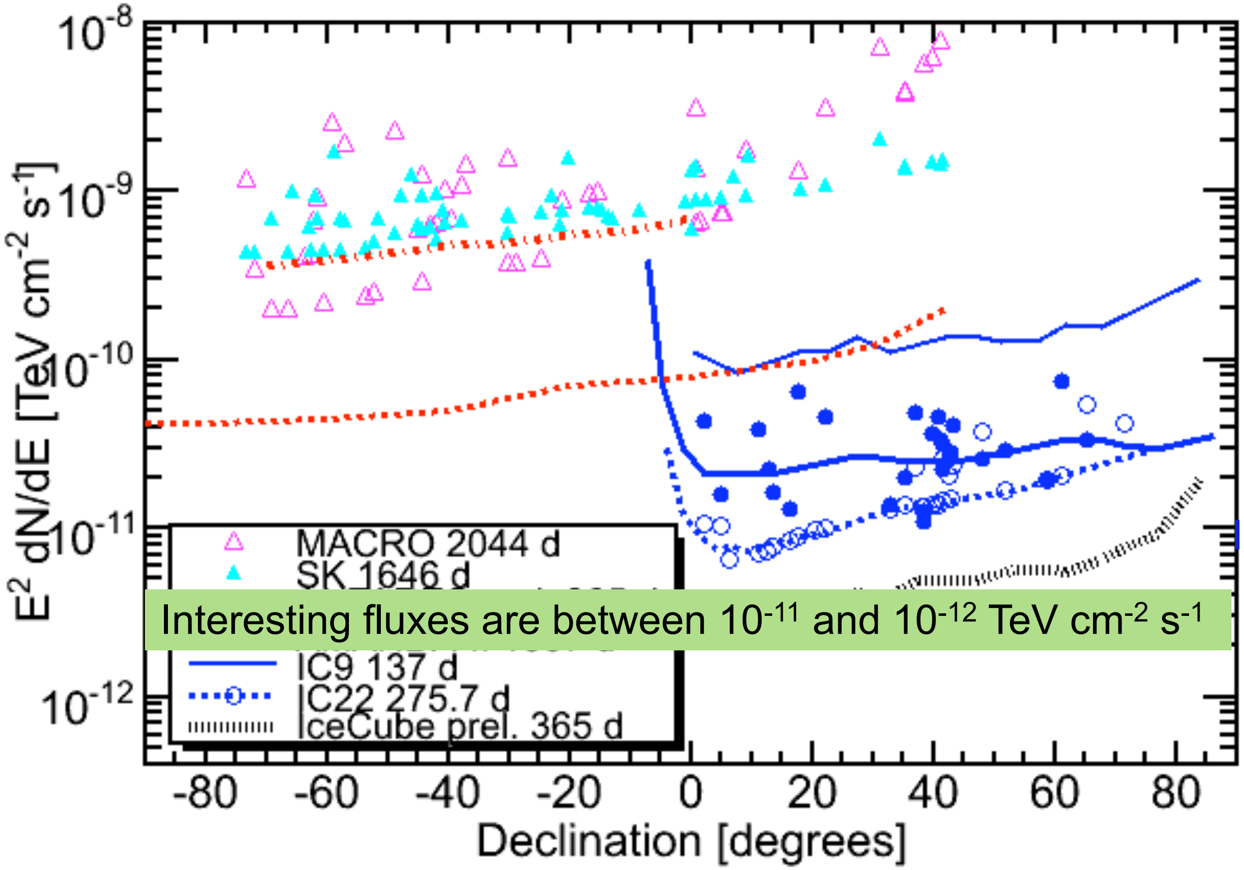
$$= 10^{-11} \sim 10^{-12}\,\frac{photons}{cm^2 s}\,\frac{W}{10^{50}\,erg}\,\frac{n}{1\,cm^3}\left(\frac{d}{1\,kpc}\right)^{-2}$$

RX J1713.7-3946
Berezhko & Völk, ICRC2007



Halzen, arxiv:0809.1874

What fluxes accessible by experiments?



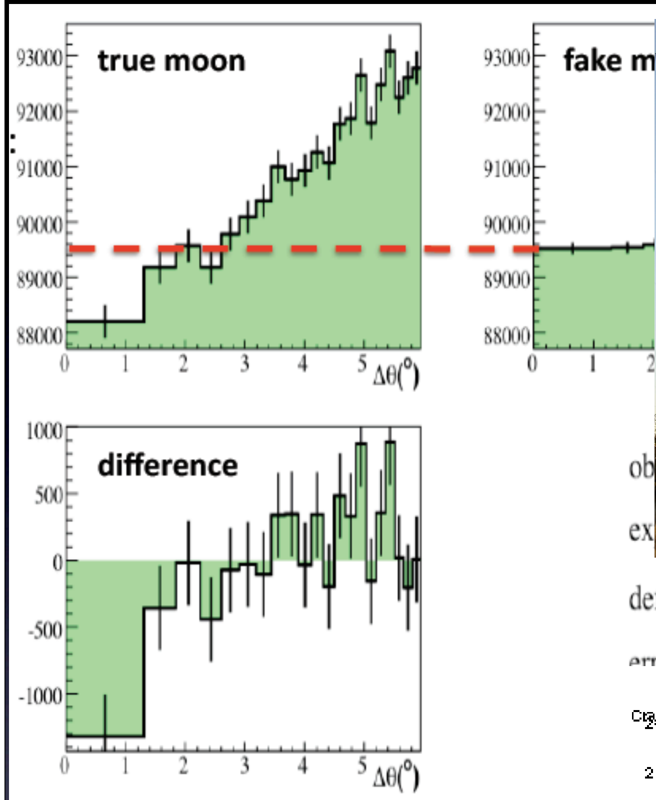
MACRO: ApJ 546, 2000
SK: Astrop. Phys 29, 2008
ANTARES, ICRC 2007
IC9, ICRC 2007
IC80, Astrop. Phys. 20, 2004

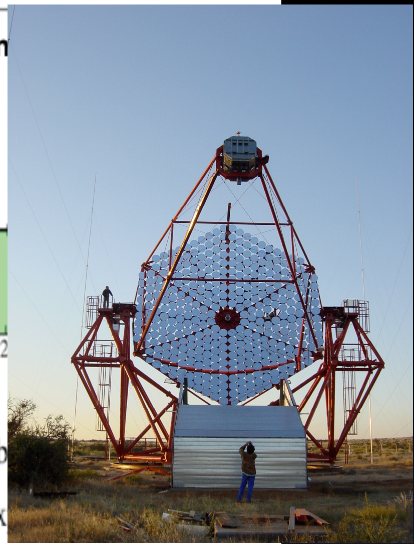
AMANDA-II 7 yr paper submitted to PRLD arXiv:0809.1646

IC22 275.7d sensitivity

IC22 almost 10 times better than IC9
IC22 factor of 3 better than AMANDA 7 yrs at the horizon

Standard candle: the moon shadow



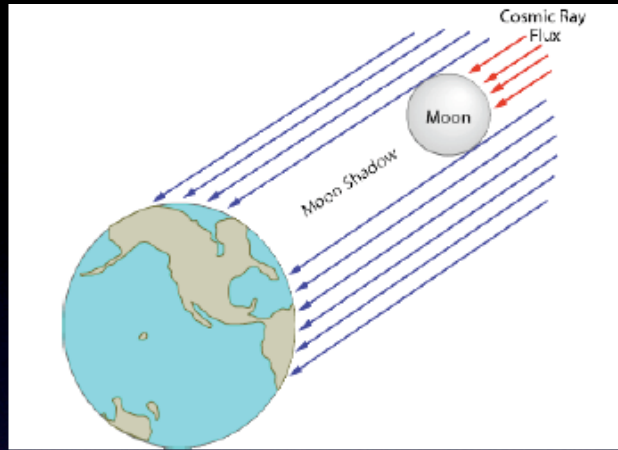


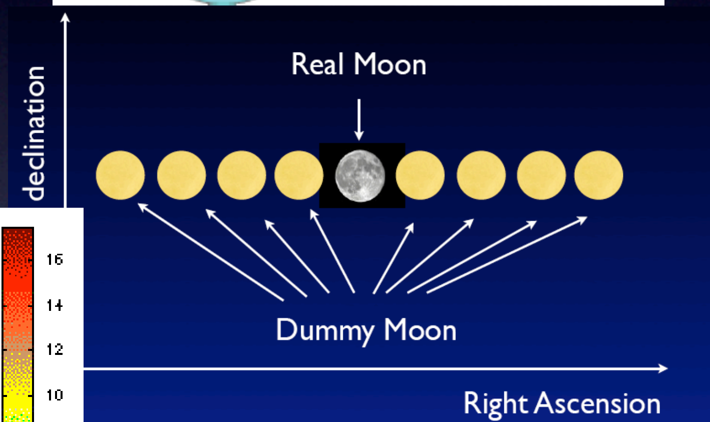
ob

ex

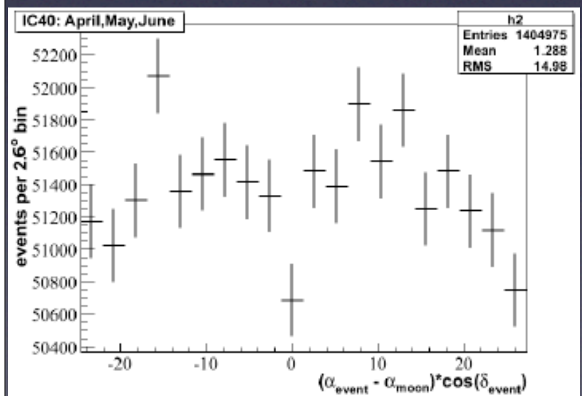
deficit: -1320 events

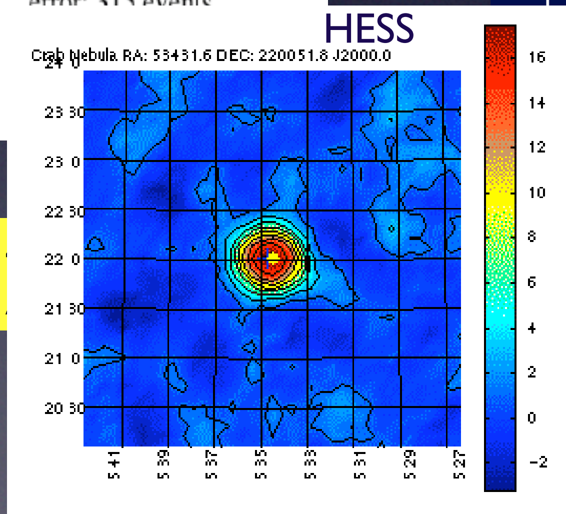
error: 315 events





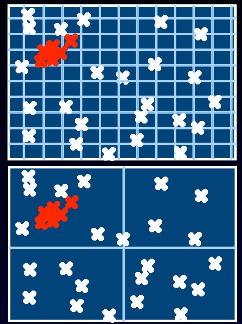
lata (better ang res).





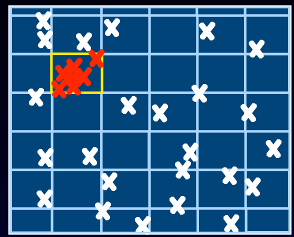
Binned/Unbinned Methods

Non optimal



Grid in the sky

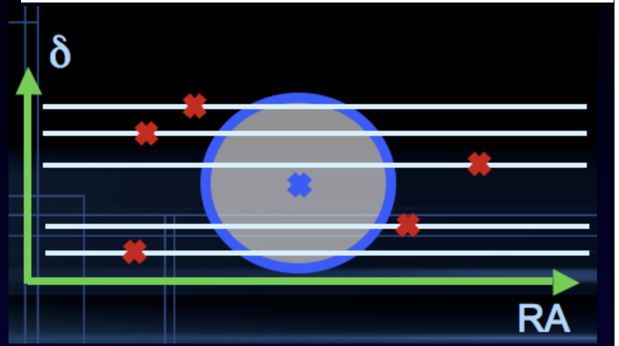
Optimization



Optimal size

Binomial statistics to get significance

Clusters around fixed directions



Maximum LH ratio (Braun et al, 2008) or Expectation Maximization pattern recognition method (Aguilars & Hernandez, 2008)

$$\mathcal{L}(n_s) = \prod_{i=1}^{N} \left(\frac{n_s}{N} \mathcal{S}_i + \left(1 - \frac{n_s}{N}\right) \mathcal{B}_i \right)$$

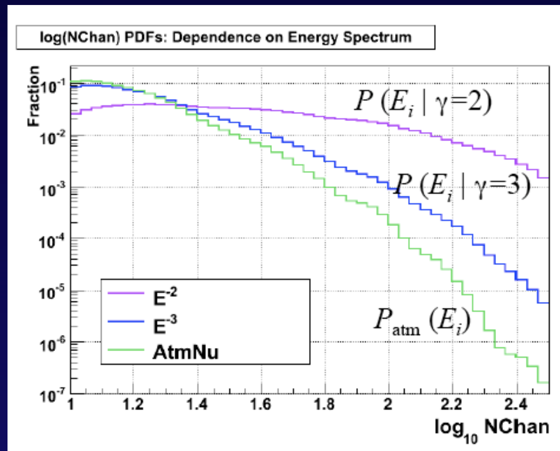
LH function = product of partial prob for each event

$$\mathcal{S}_i = \frac{1}{2\pi {\sigma_i}^2} e^{-{r_i}^2/2{\sigma_i}^2} \cdot \underline{P(E_i|\gamma)}$$

Signal pdf contains space and energy term that characterize the difference between signal and background

$$\mathcal{B}_i = B_{\text{zen}} \cdot \underline{P_{\text{atm}}(E_i)}$$

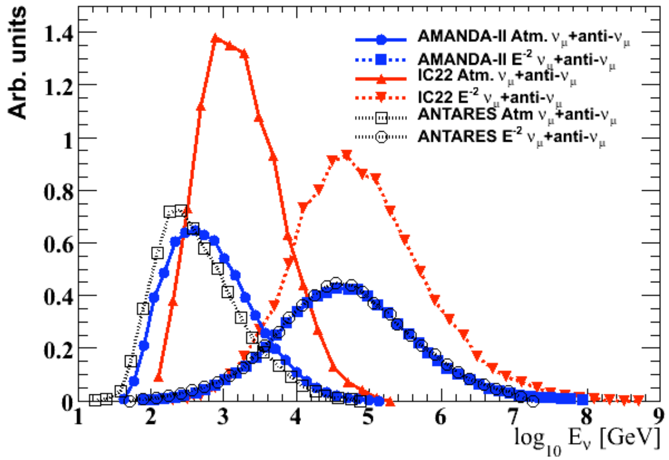
Backgr pdf is from data hence p-values do not depend on simulation

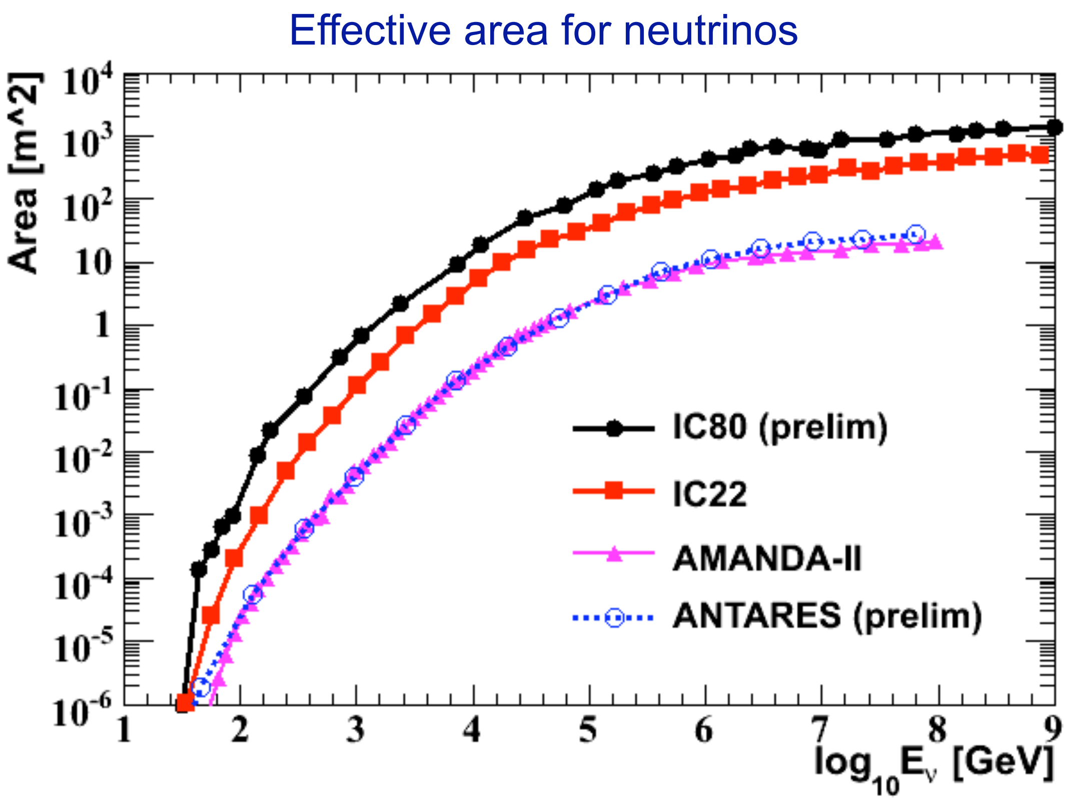


$$\log \lambda = \log \left(\frac{L(x_s, \hat{\gamma}, \hat{n}_s)}{L(n_s = 0)} \right)$$

used to determine significance of observed deviation from null hypothesis

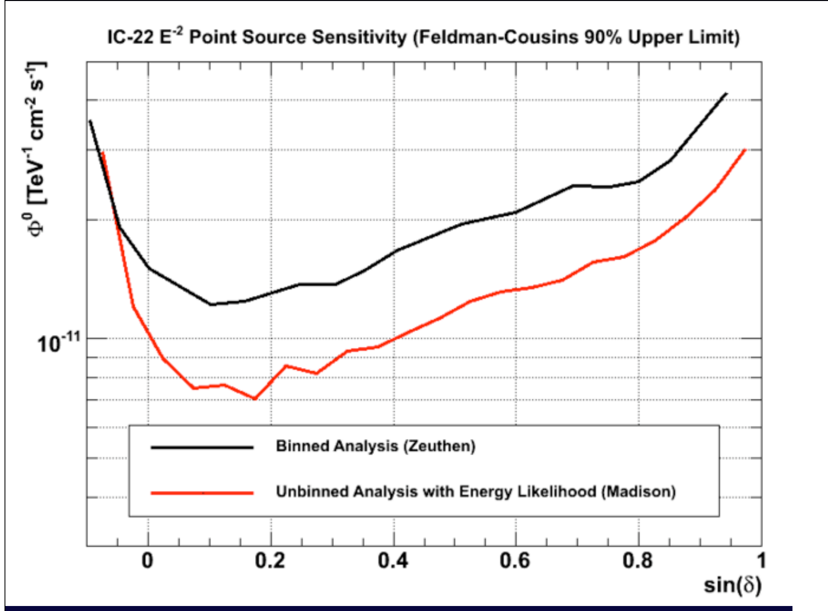
Effective areas for muon neutrinos



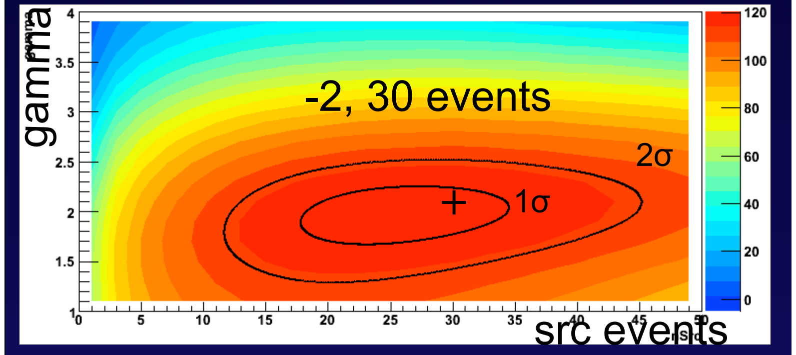


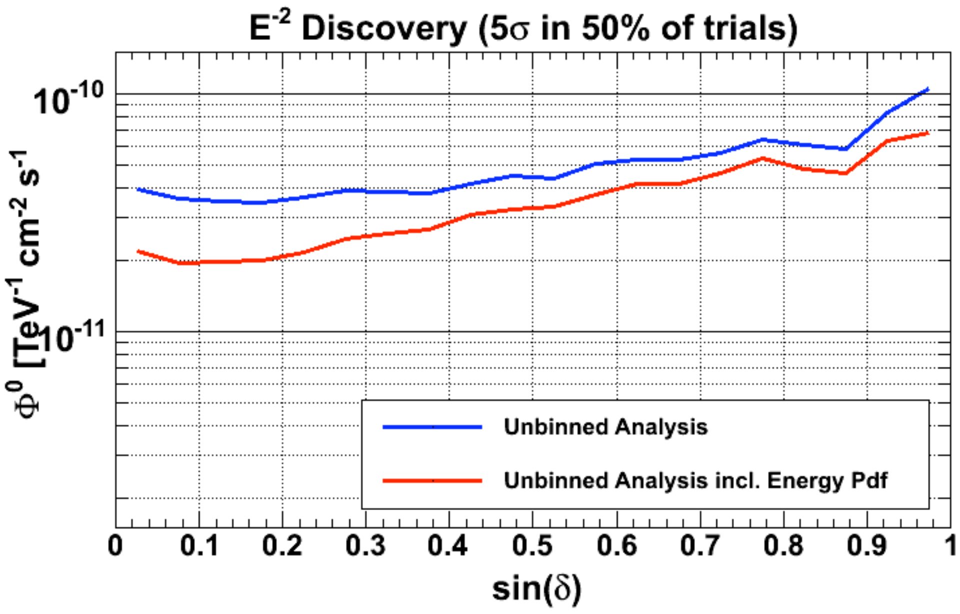
$$N_\mu = \int A_{eff}^\nu(E_\nu, \theta_\nu, \phi_\nu) \frac{d\Phi_\nu}{dE_\nu d\Omega_\nu} dE_\nu \, d\Omega_\nu$$

More powerful method



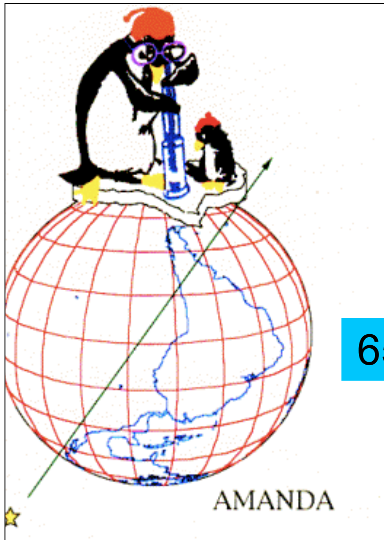
10 events from a source at 30° with E^{-2} for 5σ detection with 50% prob



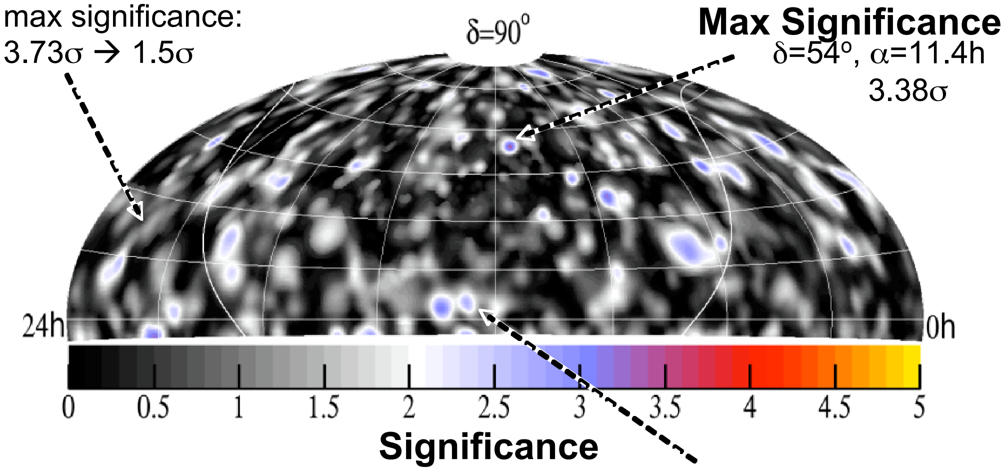


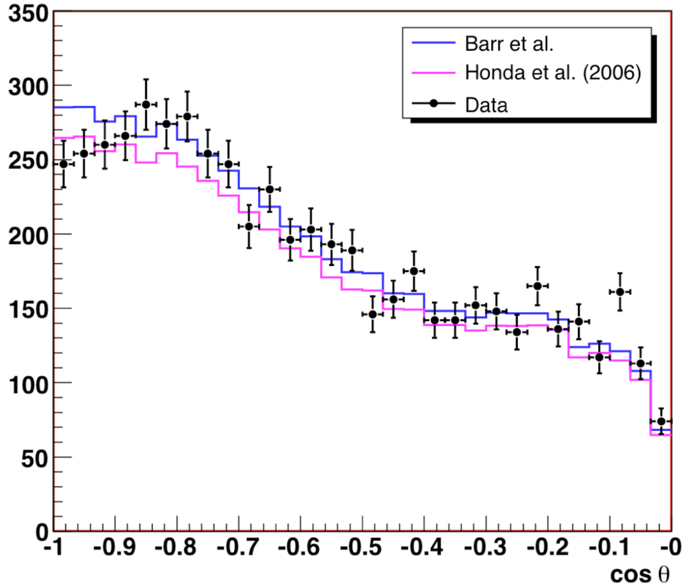
7yrs AMANDA result

arXiv:0809.1646



6595 ev/3.8 yr





95 of 100 data sets randomized in RA have a significance ≥ 3.38σ

5686 events used for testing atm nu calculations and VLI and decoherence

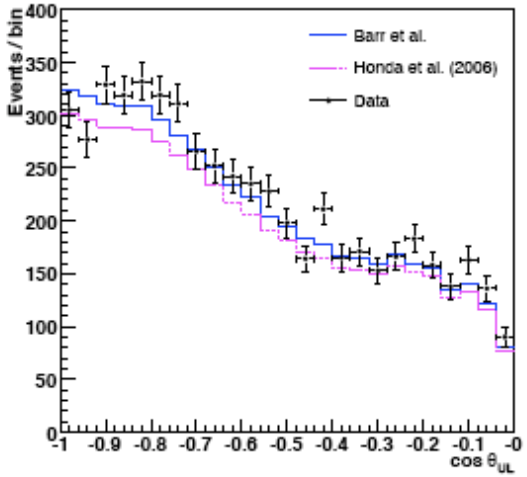
Selected Sources

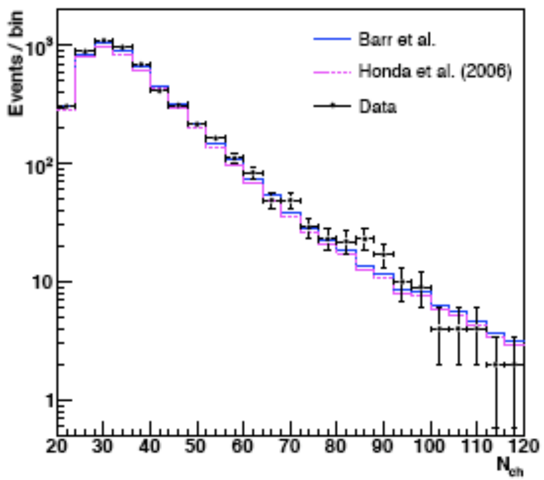
Source	μ_{90}	P-value
Crab	4.62	0.10
MGRO J2019+37	4.14	0.077
Mrk 421	0.67	0.82
Mrk 501	2.97	0.22
LS I +61 303	9.62	0.03
Geminga	10.72	0.0086

$E^2\Phi < \mu 90 * 10^{-11}$ TeV cm^{-2} s^{-1}

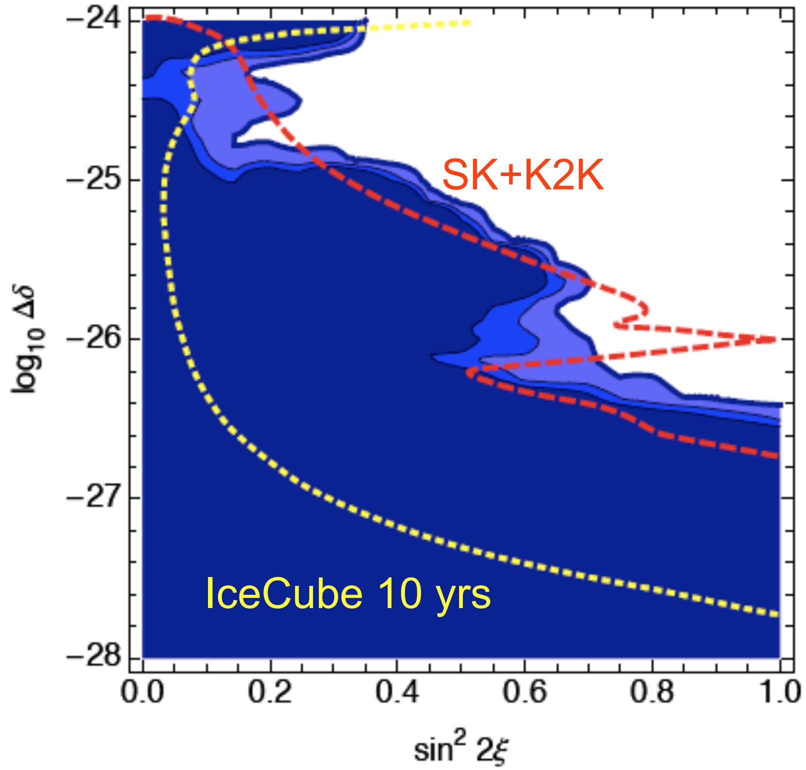
The probability of obtaining p ≤ 0.0086 for at least one of the 26 sources is 20%

Oscillations: VLI

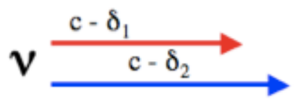




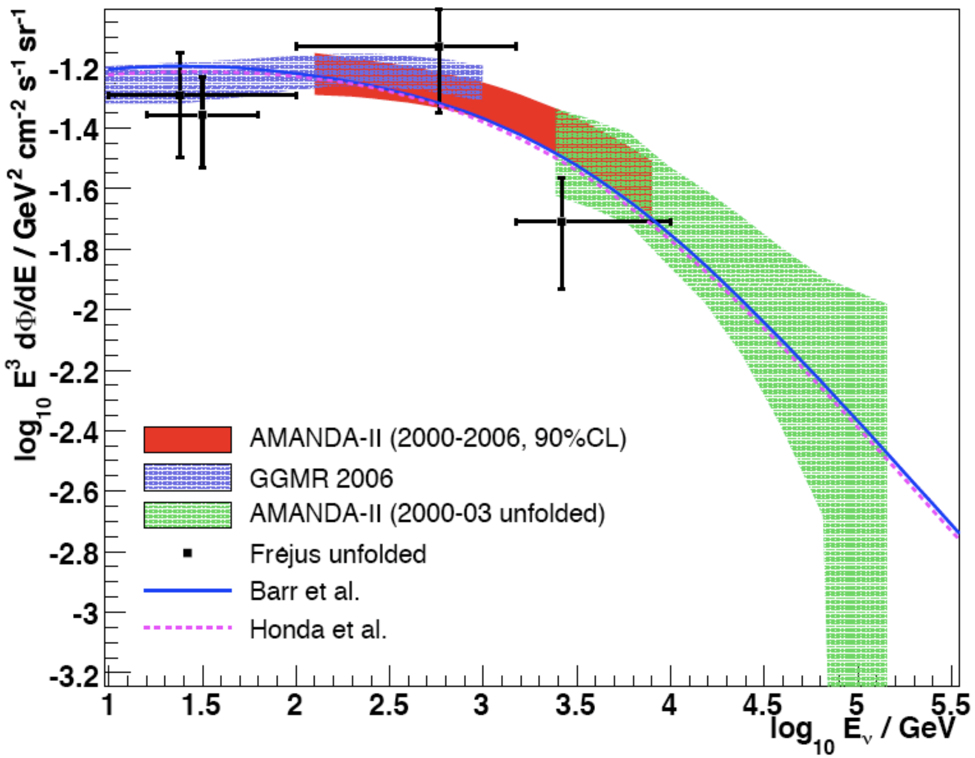
Darkest to lightest Blue: allowed regions by AMANDA 90,95.99% cl

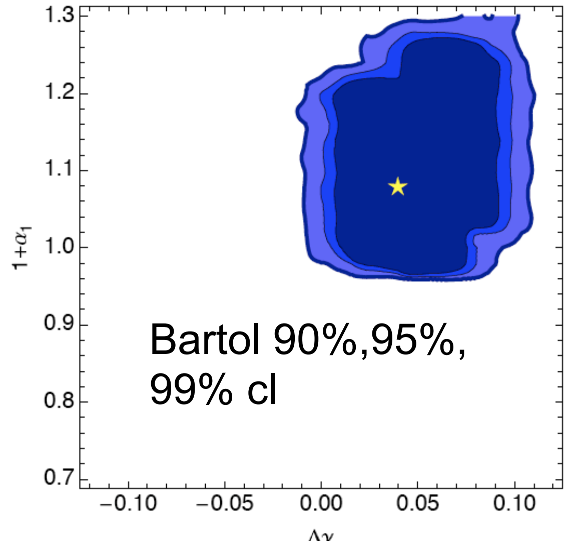


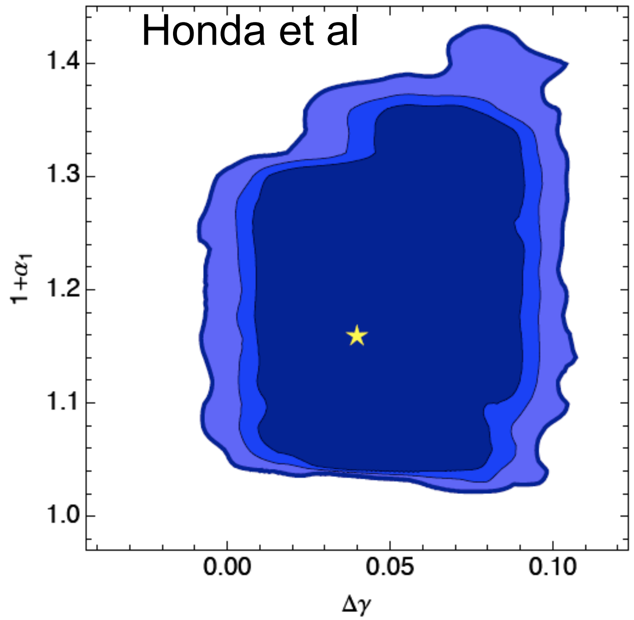
Oscillations sensitive to small energy shifts due to differences of neutrino speed compared to photon ones



Measurement of atmospheric neutrino fluxes

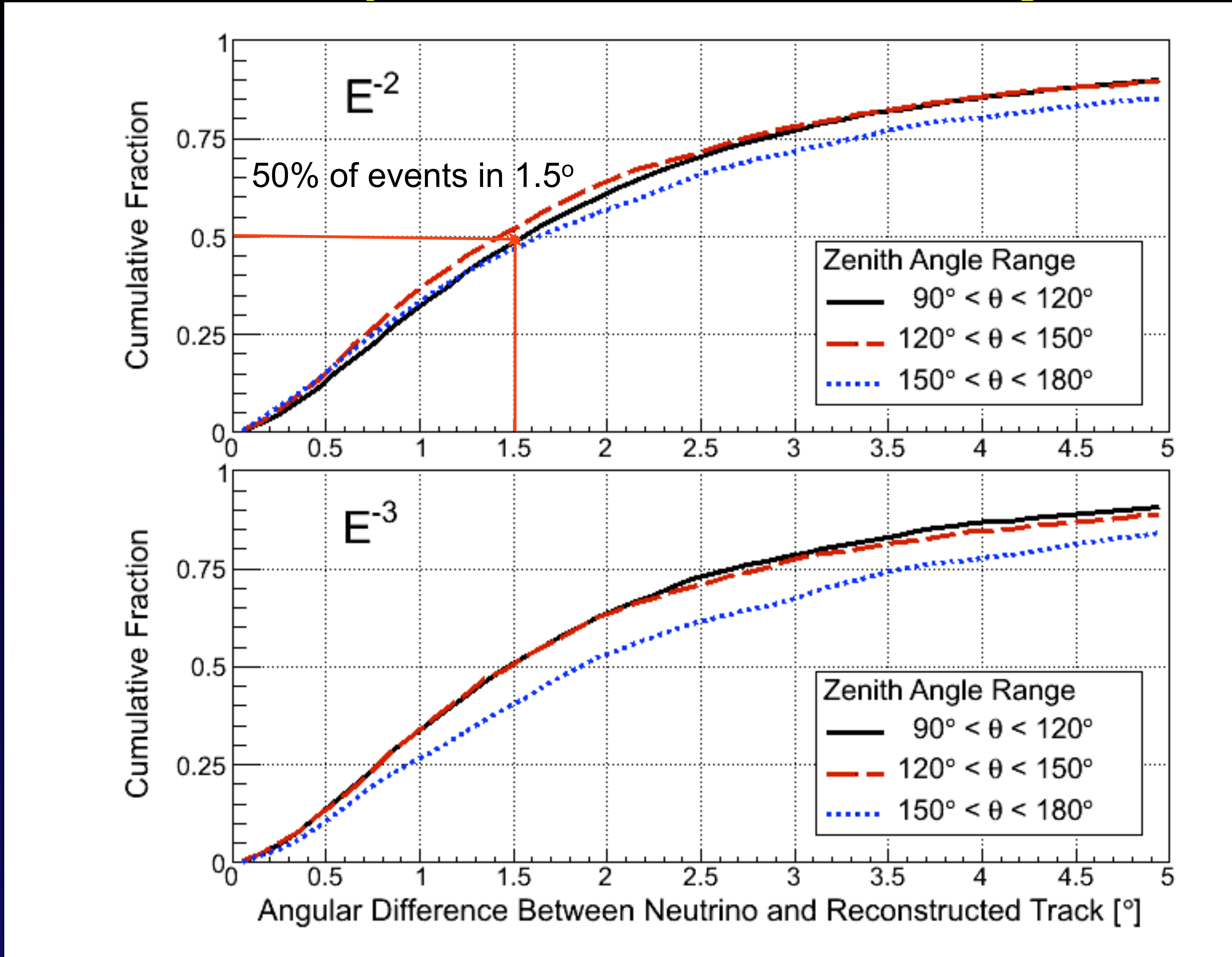






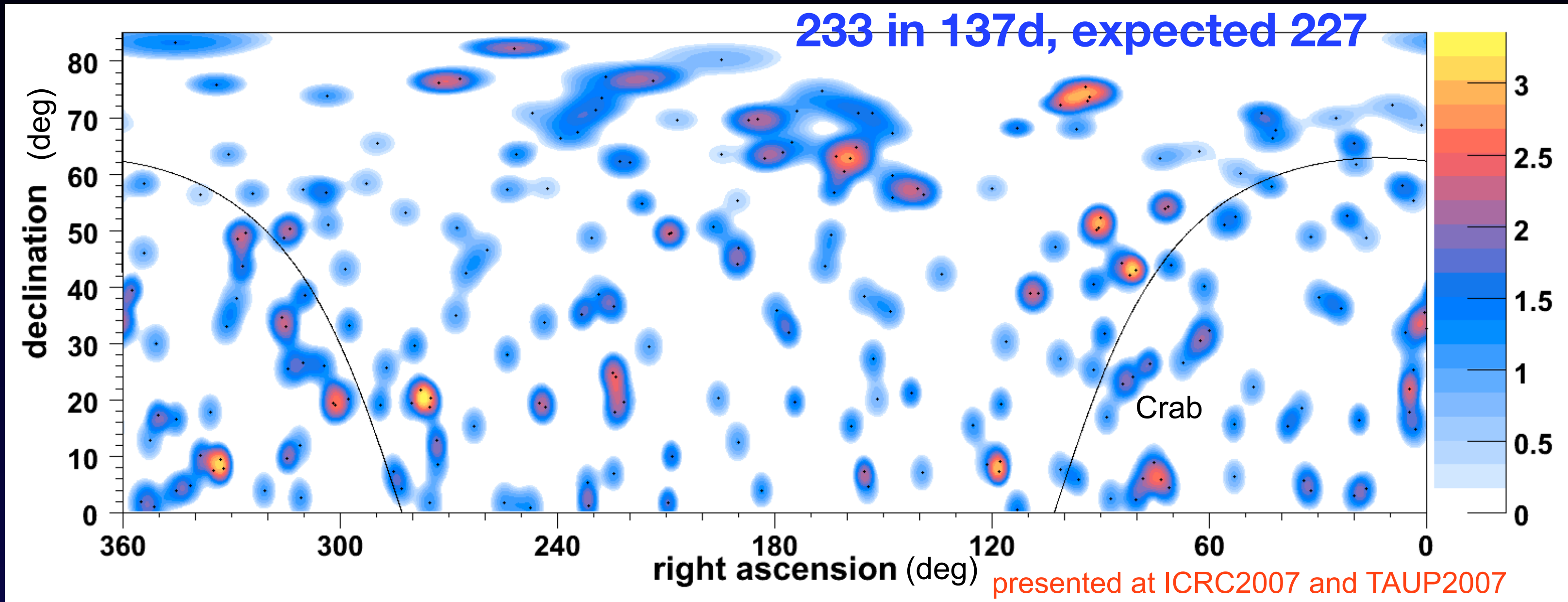
More K+ needed in these calculations to account for deep ice muons

IceCube point-source analysis



Cuts and criteria to determine p-value are predefined according in a blind way

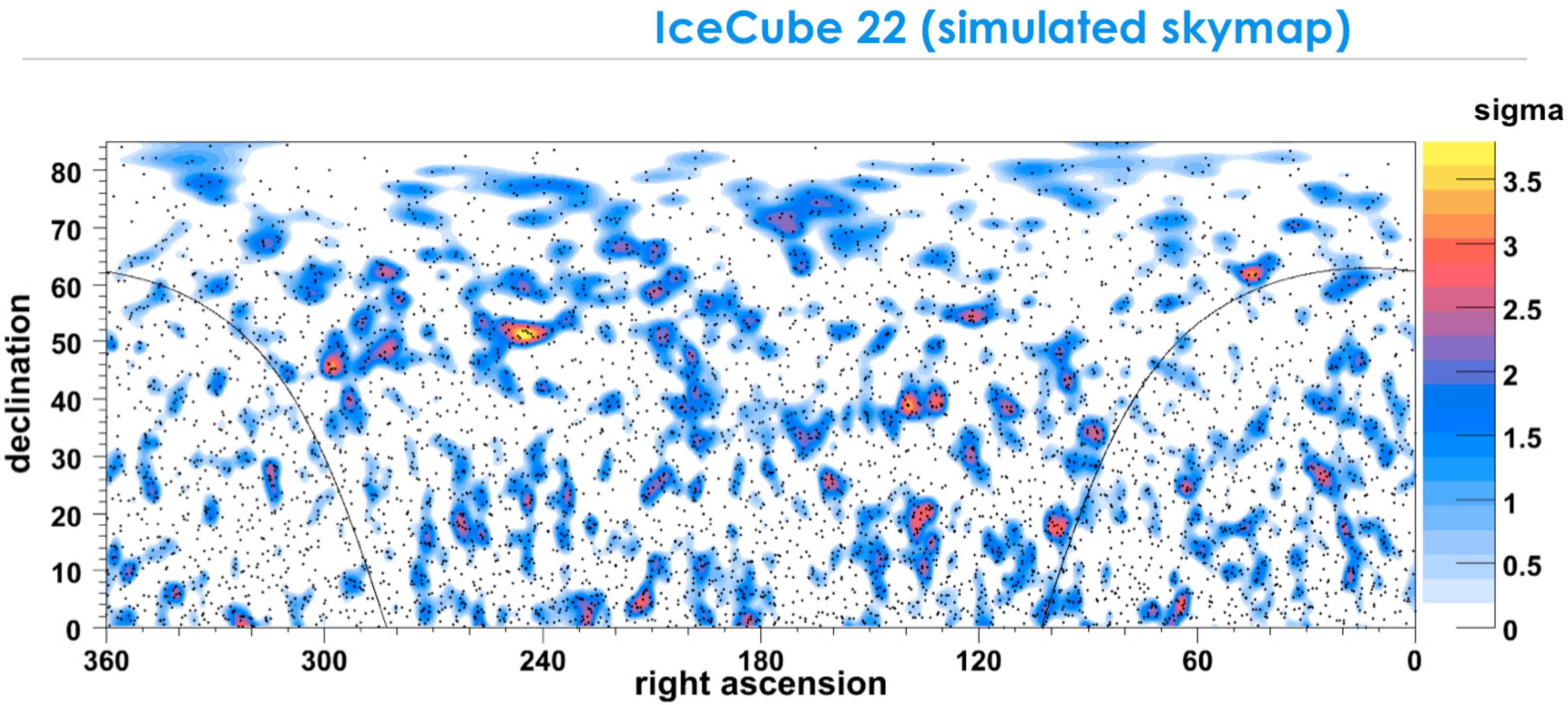
IC9 Sky Map



Max significance **3.35 sigma, 60% simulated background trials** (data scrambled in right ascension), have this significance or greater.

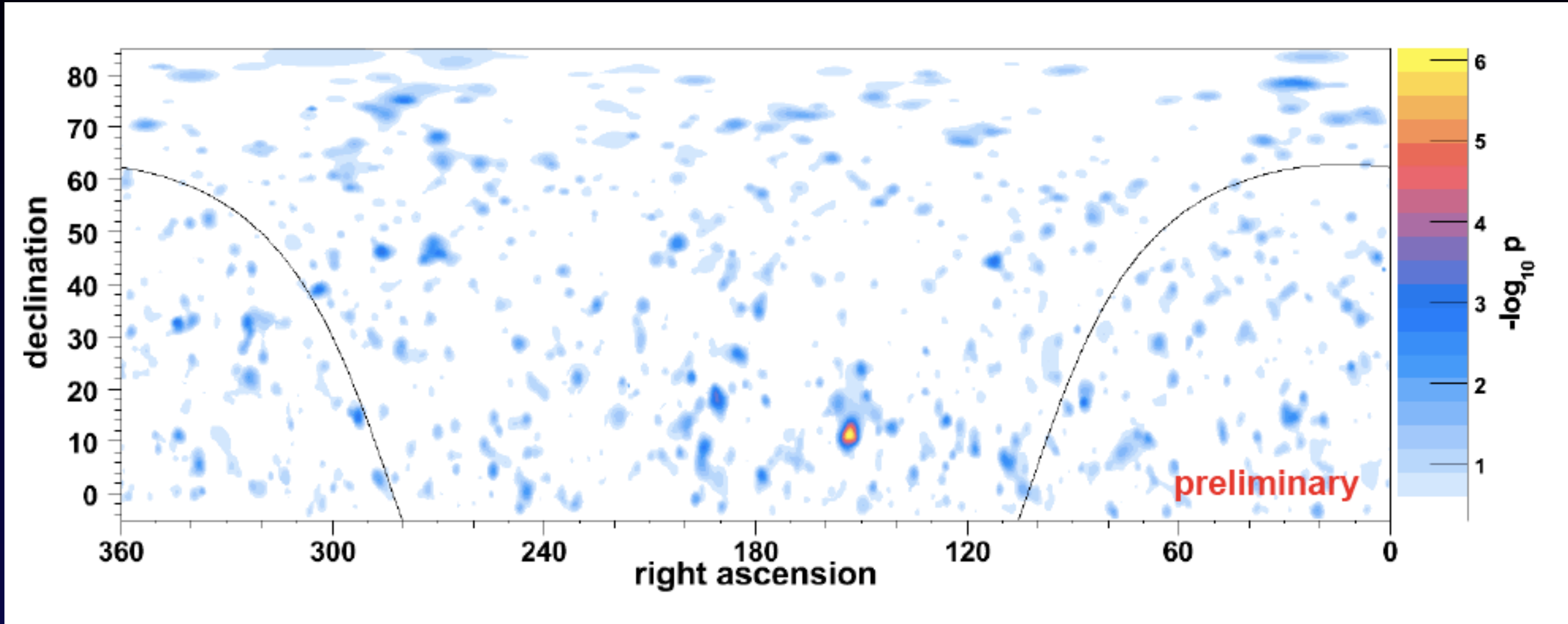
26 candidate source list: largest deviation from background: Crab 1.77 sigma, **65% of independent trials** have this significance or greater.

IC22 Sky Map



IC9 1.7 neutrino events/day, 134.7 d, median ang res 2^o
IC22: 20 events/day => 5114 at final cut level in **275.7d**
median ang res 1.5^o
IC80: expect about 200 events/day, median and res 0.8^o

IC22 unblinded Sky Map



At hottest spot: est. nSrc events = 7.7 Est. gamma = -1.65 Est. pre-trial p-value: $-\log_{10}(p) = 6.14$

Post-trial p-value: 1.34% (out of 10,000 trials of scrambled data sets 0.67% have p-value of most significant spot more significant than what found in data and we include a trial factor of 2 for having performed an all-sky analysis and a source list one)

Not seen in analysis not using energy estimator

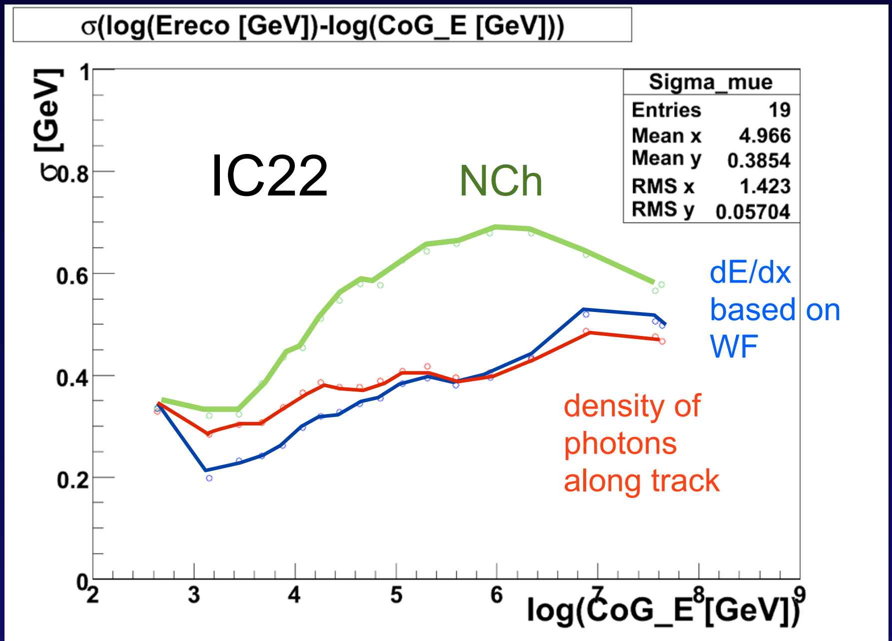
No evident candidate counterpart

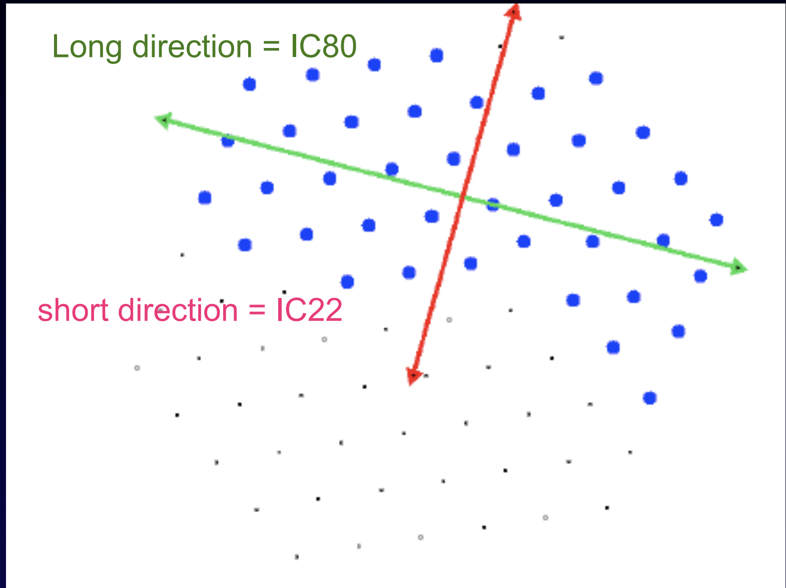
Time dependent analysis of events contributing to hottest spot. Best fit to gaussian of any duration +backg: wo energy best fit of 3.9d and with energy 71.2 d. Combined p-value = 0.6 (not significant)

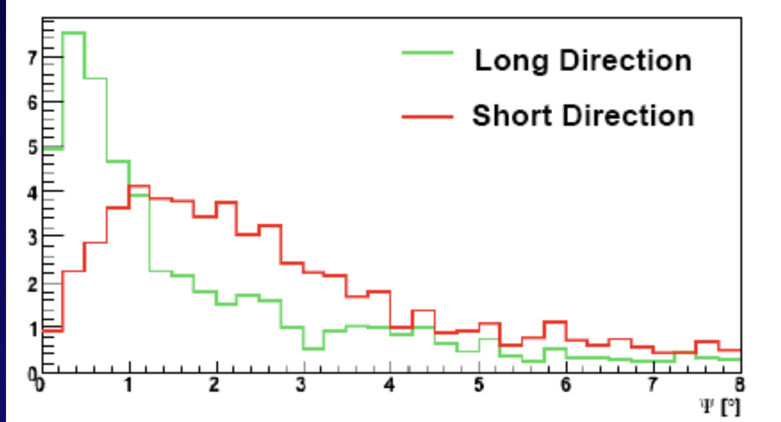
Working on:

IC40 data filtering
IC40 has improved ang. res. and about 2 x IC22 effective area

Use better track reconstruction for high NCh events (use all PE in DOMs not only first hit)
Use energy estimator rather than NCh



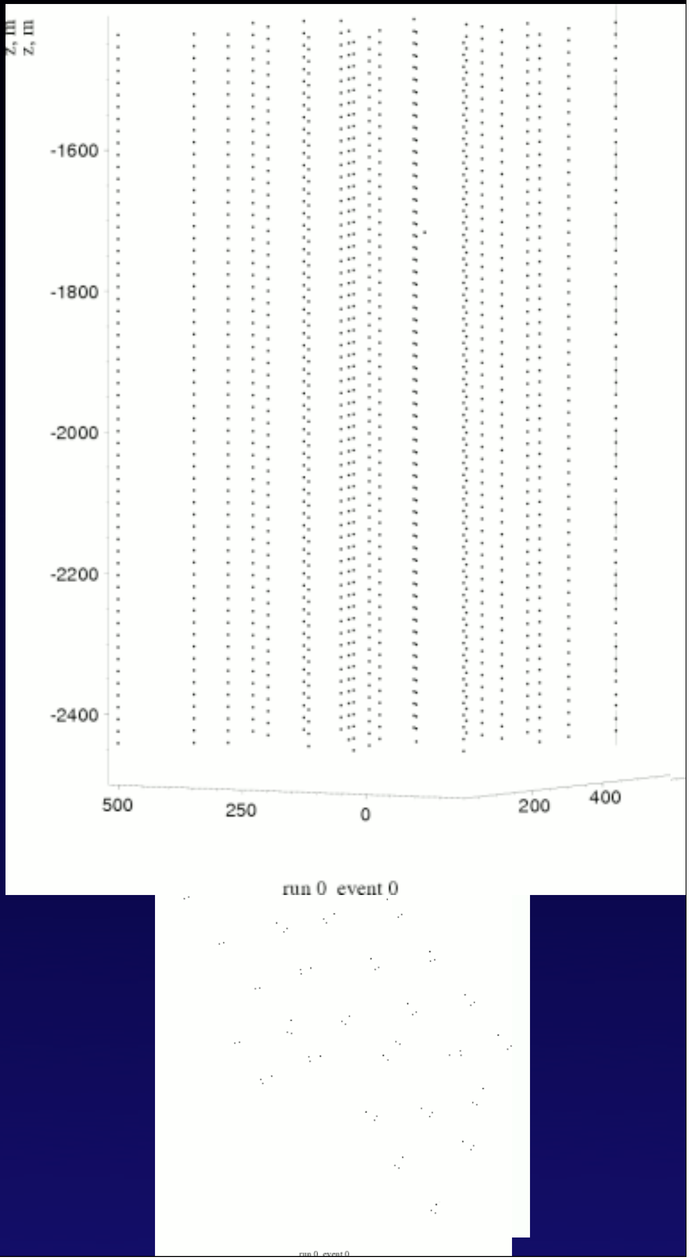




Summary

some of the hot spot events

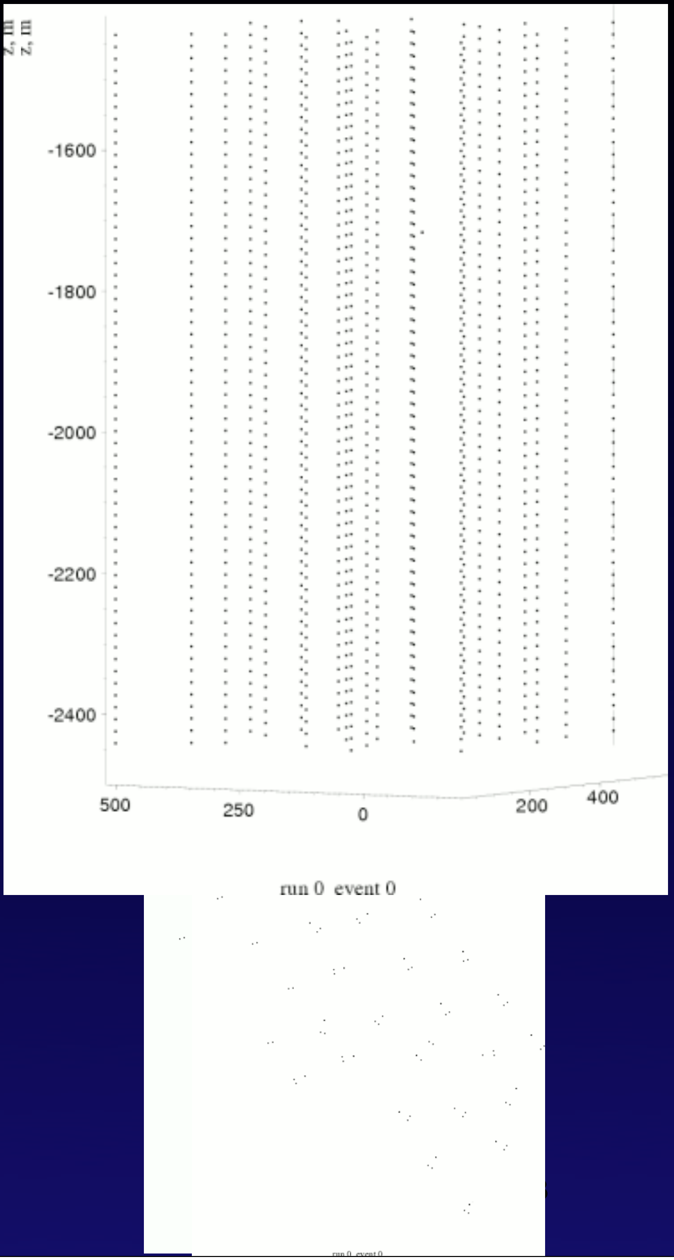
- IC22 Point-source analysis shows a hot spot at the level of 1%
- IC40 data are being filtered for physics streams and would allow to understand if it is a statistical fluctuation
- First IC56 string on Dec 6. Already 4 installed. http://driller.icecube.wisc.edu/plots/
- ANTARES if taking data in its full configuration
- Water is an ideal medium for photon propagation properties but is not a quiet environment as ice



Hottest spot events

rank	S/B	Nch	sigma (Est. Ang. res (deg))	dAng (Ang. dist. from best fit src (deg))	CogZ (Dist. det. centre - center of gravity of hits (m))
1:	67449.380	145	0.84	0.717	-349.2
2:	33656.799	148	1.75	1.086	-167.8
3:	15483.897	77	0.88	1.203	-456.1
4:	13593.747	168	2.68	1.924	-289.5
5:	4169.923	65	1.52	2.337	-285.8
6:	3199.724	51	1.62	0.444	25.6
7:	639.997	29	1.51	1.385	-198.6
8:	490.646	28	1.68	1.634	158.0
9:	308.372	44	2.79	4.595	-324.8
10:	271.344	34	1.23	2.538	139.6

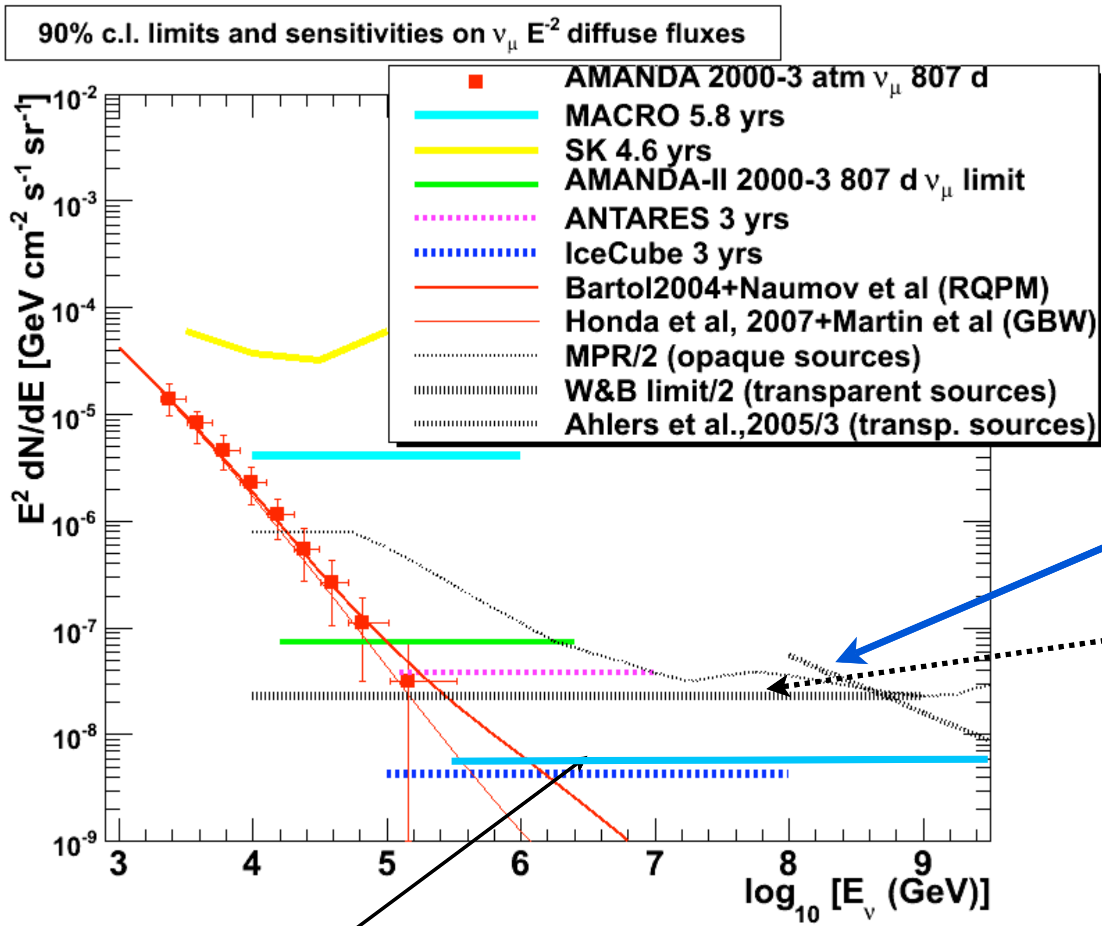
Hottest spot events are deep in the detector where the ice is more transparent and high NCh.
Signal NCh pdf affected by knowledge of ice properties but p-value extracted from data is solid.

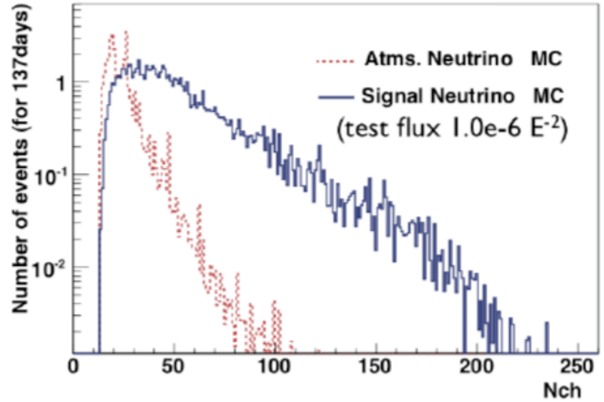


Diffuse limits

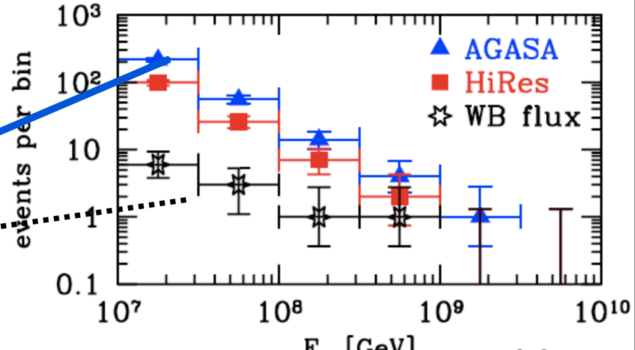
Limits assume 1:1:1 flavor ratio

AMANDA data (ICRC2007)
MACRO, Astrop. Phys 19, 2003
IC80, Astrop. Phys. 20, 2004
AMANDA, PRD76, 2007
ANTARES, ICRC2003
IC9, TAUP2007





Ahlers et al 2005

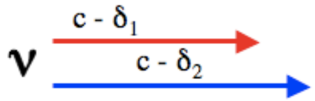


Extragal. p dominate at $10^{8.6}$ GeV rather than 10^{10} GeV

IceCube can test Auger sources (all FRI have luminosities of Cen A and M87 with evolution ~6×10^{-9} E^{-2} GeV^{-1} cm^{-2} s^{-1} sr^{-1}). Halzen & O'Murchadha, 2008

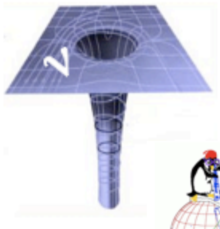
New Physics Effects

- Violation of Lorentz invariance (VLI) in string theory or loop quantum gravity*



- Violations of the equivalence principle (different gravitational coupling)†

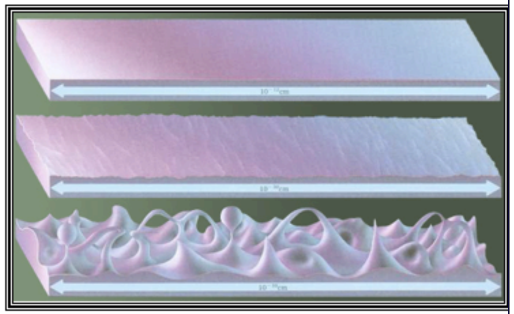
- Interaction of particles with space-time foam $\Rightarrow$ quantum decoherence of flavor states‡



* see e.g. Carroll *et al.*, PRL **87** 14 (2001), Colladay and Kostelecký, PRD **58** 116002 (1998)
† see e.g. Gasperini, PRD **39** 3606 (1989)
‡ see e.g. Anchordoqui *et al.*, hep-ph/0506168

Quantum Decoherence (QD)

Another possible low-energy signature of quantum gravity: quantum decoherence



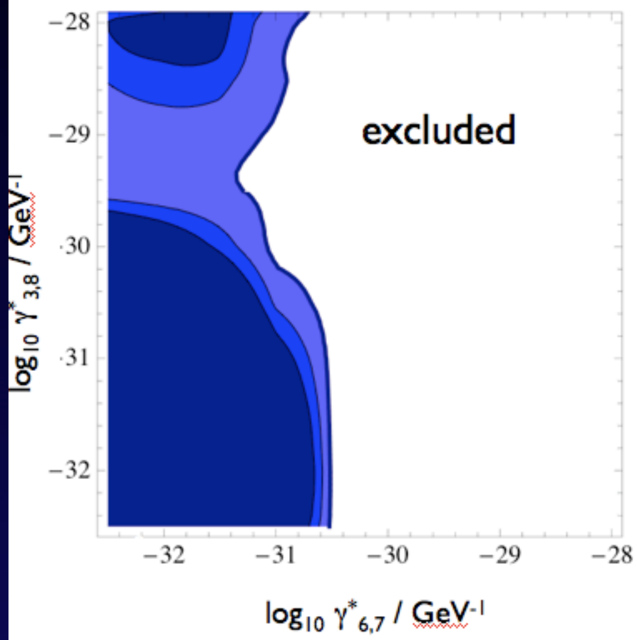
Heuristic picture: foamy structure of space-time (interactions with virtual black holes) may not preserve certain quantum numbers (like ν flavor)

Pure states interact with environment and decohere to mixed states

Systematics Summary

error	type	size	method
atm. ν flux model	norm.	±18%	MC study
σ_ν, ν-μ scattering angle	norm.	±8%	MC study
reconstruction bias	norm.	-4%	MC study
ν_τ-induced muons	norm.	+2%	MC study
charm contribution	norm.	+1%	MC study
timing residuals	norm.	±2%	5-year paper
μ energy loss	norm.	±1%	5-year paper
rock density	norm.	<1%	MC study
primary CR slope (incl. He)	slope	$\Delta\gamma$ = ±0.03	Gaisser *et al.*
charm (slope)	slope	$\Delta\gamma$ = +0.05	MC study
π/K ratio	tilt	tilt +1/-3%	MC study
charm (tilt)	tilt	tilt -3%	MC study
OM sensitivity, ice	OM sens.	sens. ±10%	MC, downgoing μ

Results: Preliminary QD limit



E² model

- SuperK limit‡ (2-flavor):

  $\gamma_i < 0.9 \times 10^{-27}$ GeV^{-1} (90% CL)

- ANTARES sensitivity* (2-flavor):

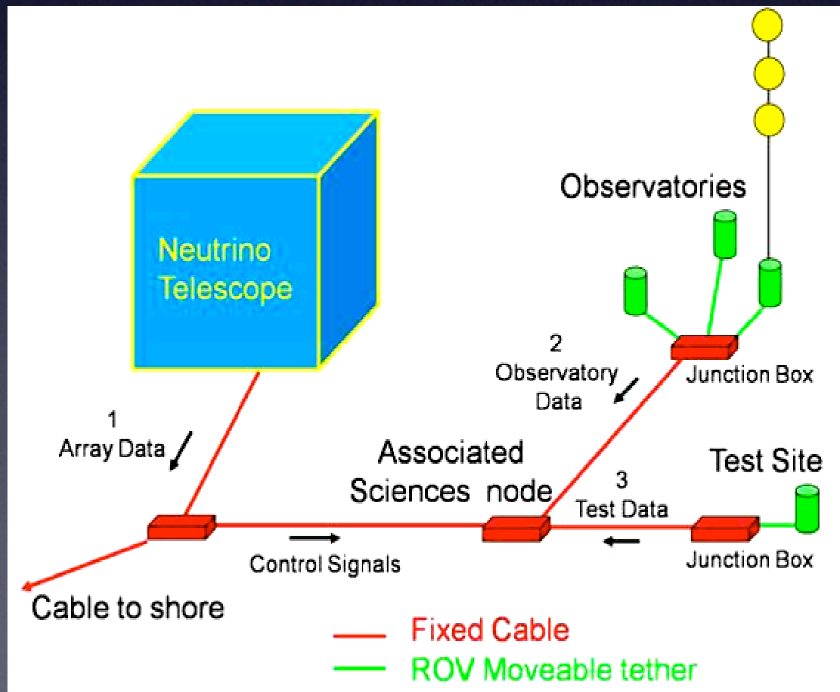
  $\gamma_i \sim 10^{-30}$ GeV^{-1} (3 years, 90% CL)

- This analysis:

  $\gamma_i < 1.3 \times 10^{-31}$ GeV^{-1} (90% CL)

* Morgan *et al.*, astro-ph/0412618
‡ Lisi, Marrone, and Montanino, PRL **85** 6 (2000)

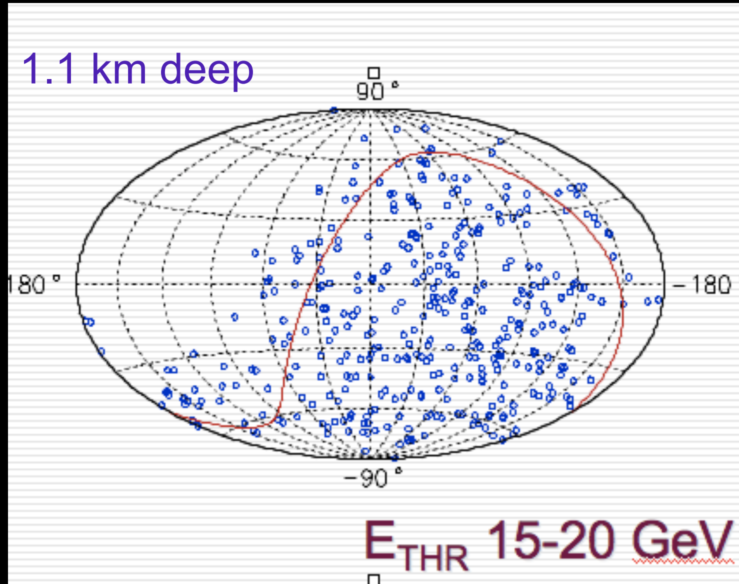
- Consortium of 40 Institutions from 10 European countries in European Strategy Forum on Reasearch Infrustructures roadmap
- Propose a facility for Deep Sea Science
- Concept Design Report done
- Site decision still open



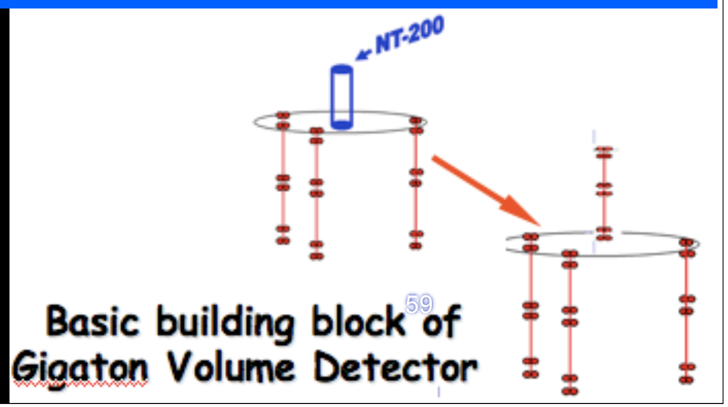
NESTOR and Baikal

Deployment of 4 floors planned in 2009
Vision: towers with 12 floors,144 PMTs/foor, 32 m diameter, 30 m between floors

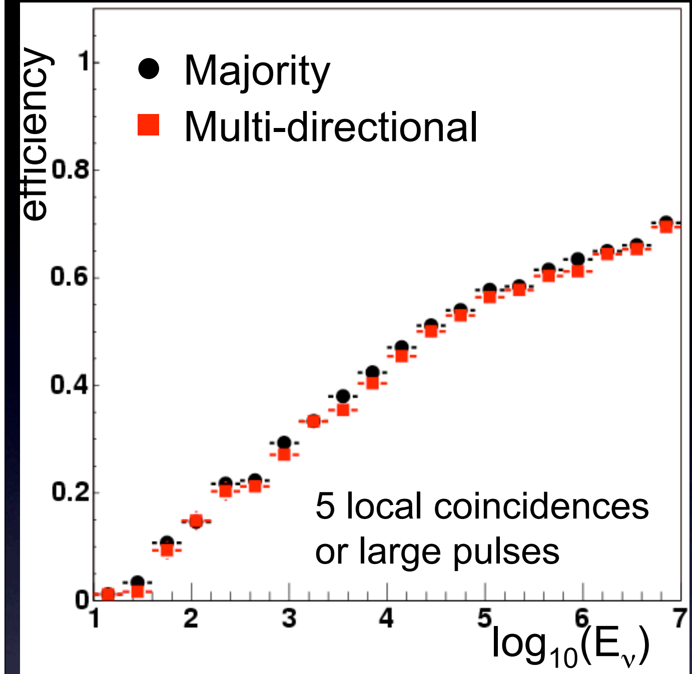
NT200 data sample: 372 neutrino events in 1038d



91-100 strings with 1300-1700 OMs
Volume for showers: 1km^3 > 100 GeV

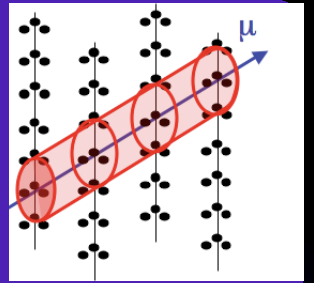


Data flow and filtering



ANTARES

All data sent to shore through Gb links and filtered looking for casual connections compatible with a muon track

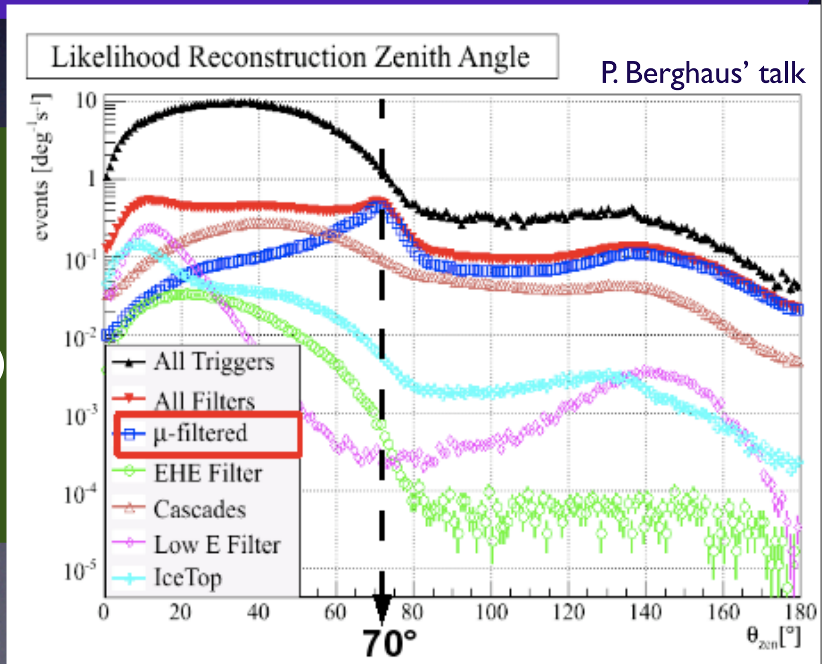


Trigger: ≥ 5 L1, causal connection between L1
L1 = LC on OM triplet in 20 ns or a > 3 pe pulse

Trigger rate: ~1 Hz (5 lines)
~2-3 Hz (10 lines)

IC22 : 35 GB/d transmitted through satellite + offline filtering in physics streams

Detector config	Phys run	Trigger rate (8DOMs in 5μs)	Neutrinos/d (analysis level)
IC9	137d	80 Hz	1.7
IC22	290d	670 Hz	20
IC40	May 08-	1.4 kHz	~40



Alvarez-Muniz and Halzen ApJ 576 (2002)

Halzen and Hooper, astro-ph/0502449

The photon $\Leftrightarrow$ neutrino connection

pp interactions

$$p + A \rightarrow \pi^0 + \pi^+ + \pi^-$$

pions share p energy

$\pi^0 \downarrow \gamma\gamma$, $\quad \pi^+ \downarrow \mu\nu_\mu \quad e + 2\nu_\mu + \nu_e$

2 photons with: $E_\gamma \approx E_\pi/2 \approx E_p/6$

For each gamma 2 muon neutrinos with:

$$E_\nu \approx E_\pi/4 \approx E_p/12$$

Hence energy in photons and gammas is the same.

After oscillations: ν_μ/γ ~0.5

$$\int_{E_\gamma^{\min}}^{E_\gamma^{\max}} E_\gamma \frac{dN_\gamma}{dE_\gamma} dE_\gamma = K \int_{E_\nu^{\min}}^{E_\nu^{\max}} E_\nu \frac{dN_\nu}{dE_\nu} dE_\nu,$$

K~0.5

$$E_p^{\max} = 6E_\gamma^{\max}, \quad E_\nu^{\max} = \frac{1}{12} E_p^{\max},$$

$$E_p^{\min} = \Gamma \frac{(2m_p + m_\pi)^2 - 2m_p^2}{2m_p} \simeq \Gamma \times 1.23 \text{ GeV},$$

$$p + p \rightarrow p + p + \pi^0$$

$$p + p \rightarrow p + n + \pi^+$$

Minimum proton energy fixed by threshold for π production (Γ =E/m is the Lorentz factor of the p jet respect to the observer)

The photon ⇔ neutrino connection

pγ interactions

$$1)\, p+\gamma \rightarrow \Delta^+ \rightarrow p\pi^0$$
$$2)\, p+\gamma \rightarrow \Delta^+ \rightarrow n\pi^+$$

BR = 2/3
BR = 1/3

E of gammas in lab (p at rest)

$$E_{k,p} = \frac{\left(\sum_f M_f\right)^2 - (m_t + m_p)^2}{2m_t} = \frac{(m_N + m_\pi)^2 - m_p^2}{2m_p} \sim 150 \text{ MeV}$$

$$E_\gamma = \gamma_p \varepsilon_\gamma = 150\text{MeV}$$

Energy of gammas p rest frame

Energy of gammas in CM

$$E_{p,thr} = \gamma_p m_p = 150\,MeV \times m_p / \varepsilon_\gamma = \left(\frac{1MeV}{\varepsilon_\gamma}\right) \times 150\,GeV$$

2 gammas with 2/3 x 0.1 E_p = 4/3 x 0.1 E_p
2 muon neutrinos (if muon decays) with 1/3 x 0.1E_p/2 = 1/3 x 0.1 E_p

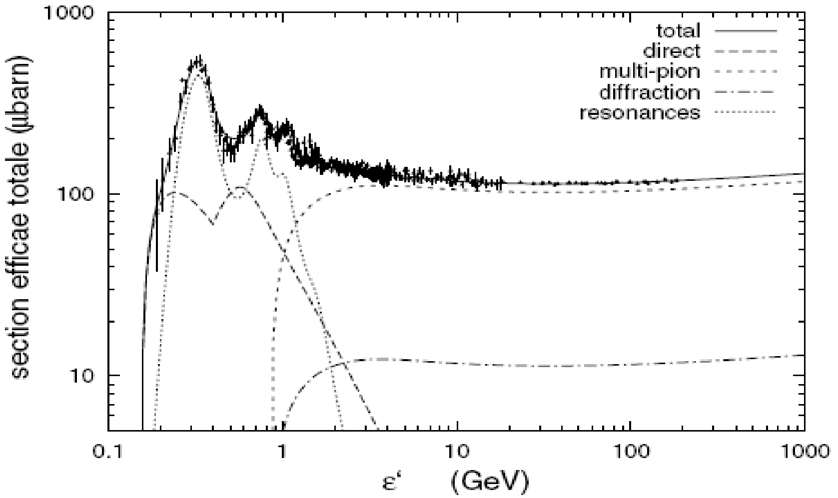
$$E_\gamma = \frac{E_p < x_{p\to\pi} >}{2} = 10\% E_p$$

$$E_\nu = \frac{E_p < x_{p\to\pi} >}{4} = 5\% E_p$$

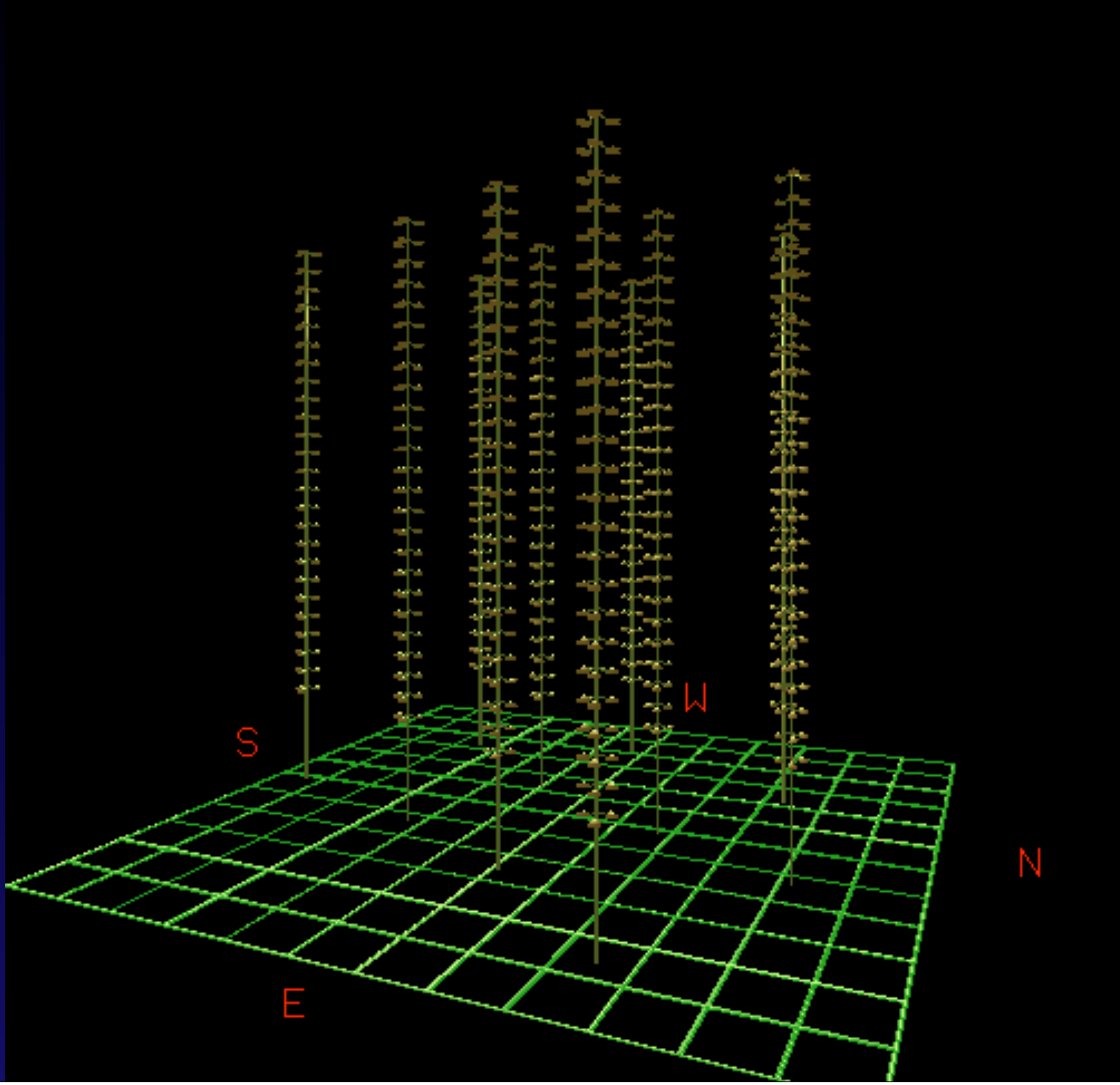
$$< x_{p\to\pi} > \approx 0.2$$

$$\int_{E_{\gamma\,\min}}^{E_{\gamma\,\max}} E_\gamma \frac{dN_\gamma}{dE_\gamma} dE_\gamma = K \int_{E_{\nu\,\min}}^{E_{\nu\,\max}} E_\nu \frac{dN_\nu}{dE_\nu} dE_\nu$$

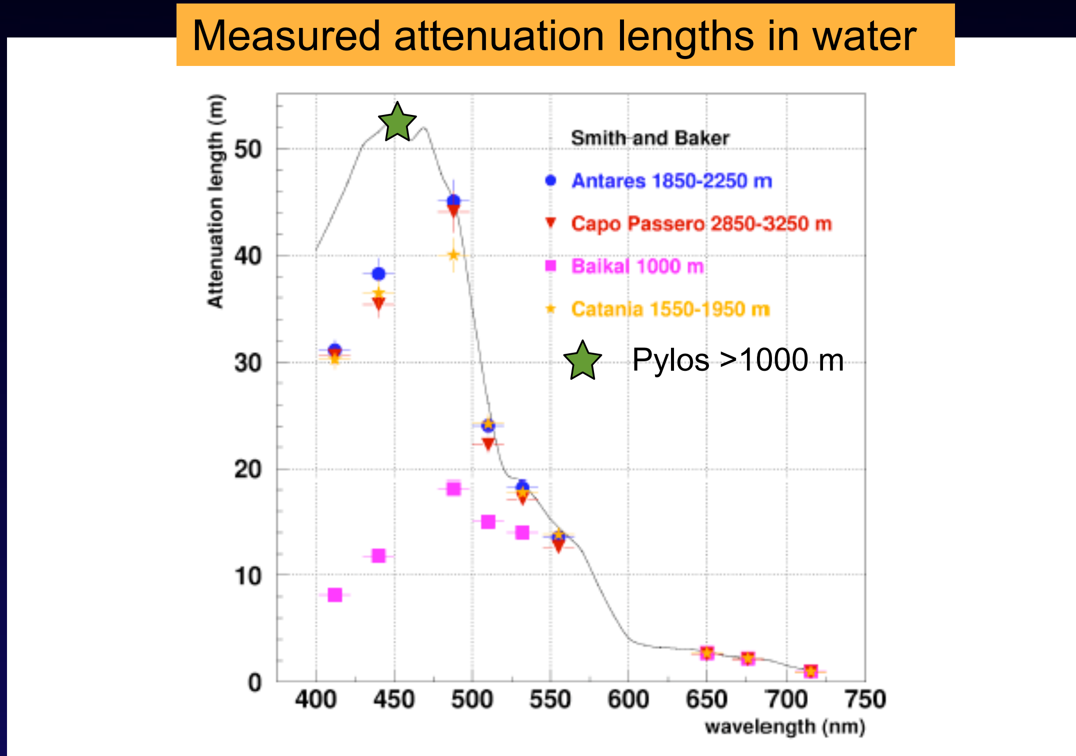
K ≈ 2 after oscillations are accounted for



ANTARES 10 line event



Attenuation length in water



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