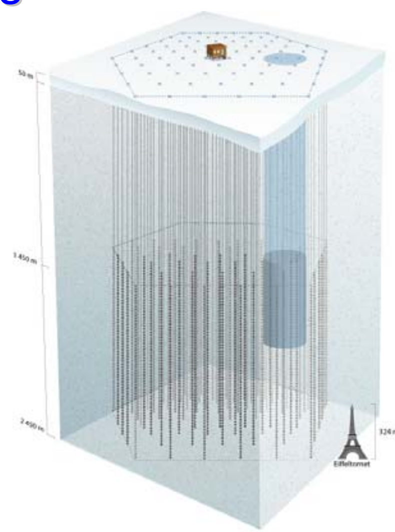
Neutrino Astronomy with IceCube

- Why Neutrino Astronomy
  - Source of UHE cosmic rays
  - Supernova Remnants
  - AGN / μQuasars
  - GRBs
  - GZK Cutoff
  - Dark Matter
- IceCube
  - Neutrino Detection in Ice
  - Amanda Results
  - IceCube Status and Performance
- Life at the South Pole



THE ICECUBE COLLABORATION

USA:
- Bartol Research Institute, Delaware
- Univ. of Alabama
- Pennsylvania State University
- UC Berkeley
- UC Irvine
- Clark-Atlanta University
- University of Maryland
- IAS, Princeton
- University of Wisconsin-Madison
- University of Wisconsin-River Falls
- Lawrence Berkeley National Lab.
- University of Kansas
- Southern University and A&M College, Baton Rouge
- University of Alaska, Anchorage

Sweden:
- Uppsala Universitet
- Stockholm Universitet

UK:
- Imperial College, London
- Oxford University

Netherlands:
- Utrecht University

Germany:
- Universität Mainz
- DESY-Zeuthen
- Universität Dortmund
- Universität Wuppertal
- Universität Berlin
- MPI Heidelberg
- RWTH Aachen

Belgium:
- Université Libre de Bruxelles
- Vrije Universiteit Brussel
- Universiteit Gent
- Université de Mons-Hainaut

Japan:
- Chiba university

New Zealand:
- University of Canterbury

(The IceCube Collaboration now includes AMANDA)

The IceCube Collaboration

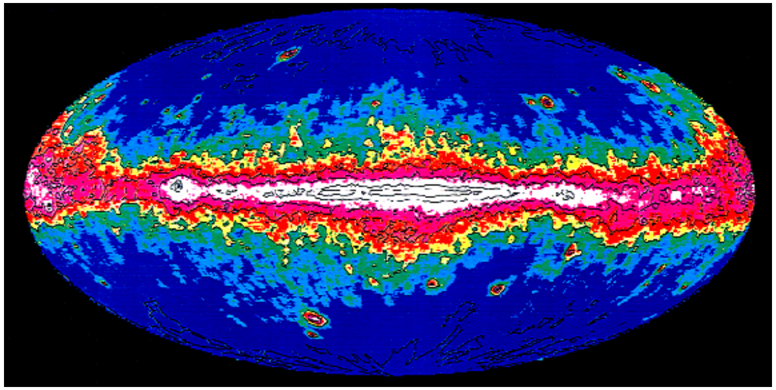
A. Achterberg[31], M. Ackermann[33], J. Adams[11], J. Ahrens[21], K. Andeen[20], D. W. Atlee[29], J. N. Bahcall[25,a], X. Bai[23], B. Baret[9], M. Bartelt[13], S. W. Barwick[16], R. Bay[5], K. Beattie[7], T. Becka[21], J. K. Becker[13], K.-H. Becker[32], P. Berghaus[8], D. Berley[12], E. Bernardini[33], D. Bertrand[8], D. Z. Besson[17], E. Blaufuss[12], D. J. Boersma[20], C. Bohm[27], J. Bolmont[33], S. Böser[33], O. Botner[30], A. Bouchta[30], J. Braun[20], C. Burgess[27], T. Burgess[27], T. Castermans[22], D. Chirkin[7], B. Christy[12], J. Clem[23], D. F. Cowen[29,28], M. V. D'Agostino[5], A. Davour[30], C. T. Day[7], C. De Clercq[9], L. Demirörs[23], F. Descamps[14], P. Desiati[20], T. DeYoung[29], J. C. Diaz-Velez[20], J. Dreyer[13], J. P. Dumm[20], M. R. Duvoort[31], W. R. Edwards[7], R. Ehrlich[12], J. Eisch[26], R. W. Ellsworth[12], P. A. Evenson[23], O. Fadiran[3], A. R. Fazely[4], T. Feser[21], K. Filimonov[5], B. D. Fox[29], T. K. Gaisser[23], J. Gallagher[19], R. Ganugapati[20], H. Geenen[32], L. Gerhardt[16], A. Goldschmidt[7], J. A. Goodman[12], R. Gozzini[21], S. Grullon[20], A. Groß[15], R. M. Gunasingha[4], M. Gurtner[32], A. Hallgren[30], F. Halzen[20], K. Han[11], K. Hanson[20], D. Hardtke[5], R. Hardtke[26], T. Harenberg[32], J. E. Hart[29], T. Hauschildt[23], D. Hays[7], J. Heise[31], K. Helbing[32], M. Hellwig[21], P. Herquet[22], G. C. Hill[20], J. Hodges[20], K. D. Hoffman[12], B. Hommez[14], K. Hoshina[20], D. Hubert[9], B. Hughey[20], P. O. Hulth[27], K. Hultqvist[27], S. Hundertmark[27], J.-P. Hülß[32], A. Ishihara[20], J. Jacobsen[7], G. S. Japaridze[3], H. Johansson[27], A. Jones[7], J. M. Joseph[7], K.-H. Kampert[32], A. Karle[20], H. Kawai[10], J. L. Kelley[20], M. Kestel[29], N. Kitamura[20], S. R. Klein[7], S. Klepser[33], G. Kohnen[22], H. Kolanoski[6], L. Köpke[21], M. Krasberg[20], K. Kuehn[16], H. Landsman[20], H. Leich[33], I. Liubarsky[18], J. Lundberg[30], J. Madsen[26], K. Mase[10], H. S. Matis[7], T. McCauley[7], C. P. McParland[7], A. Meli[13], T. Messarius[13], P. Mészáros[29,28], H. Miyamoto[10], A. Mokhtarani[7], T. Montaruli[20,b], A. Morey[5], R. Morse[20], S. M. Movit[28], K. Münich[13], R. Nahnhauer[33], J. W. Nam[16], P. Nießen[23], D. R. Nygren[7], H. Ögelman[20], A. Olivas[12], S. Patton[7], C. Peña-Garay[25], C. Pérez de los Heros[30], A. Piegsa[21], D. Pieloth[33], A. C. Pohl[30,c], R. Porrata[5], J. Pretz[12], P. B. Price[5], G. T. Przybylski[7], K. Rawlins[2], S. Razzaque[29,28], F. Refflinghaus[13], E. Resconi[15], W. Rhode[13], M. Ribordy[22], A. Rizzo[9], S. Robbins[32], P. Roth[12], C. Rott[29], D. Rutledge[29], D. Ryckbosch[14], H.-G. Sander[21], S. Sarkar[24], S. Schlenstedt[33], T. Schmidt[12], D. Schneider[20], D. Seckel[23], S. H. Seo[29], S. Seunarine[11], A. Silvestri[16], A. J. Smith[12], M. Solarz[5], C. Song[20], J. E. Sopher[7], G. M. Spiczak[26], C. Spiering[33], M. Stamatikos[20], T. Stanev[23], P. Steffen[33], T. Stezelberger[7], R. G. Stokstad[7], M. C. Stoufer[7], S. Stoyanov[23], E. A. Strahler[20], T. Straszheim[12], K.-H. Sulanke[33], G. W. Sullivan[12], T. J. Sumner[18], I. Taboada[5], O. Tarasova[33], A. Tepe[32], L. Thollander[27], S. Tilav[23], M. Tluczykont[33], P. A. Toale[29], D. Turčan[12], N. van Eijndhoven[31], J. Vandenbroucke[5], A. Van Overloop[14], B. Voigt[33], W. Wagner[13], C. Walck[27], H. Waldmann[33], M. Walter[33], Y.-R. Wang[20], C. Wendt[20], C. H. Wiebusch[1], G. Wikström[27], D. R. Williams[29], R. Wischnewski[33], H. Wissing[1], K. Woschnagg[5], X. W. Xu[4], G. Yodh[16], S. Yoshida[10], J. D. Zornoza[20,d]

1. RWTH Aachen University
2. University of Alaska Anchorage
3. CTSPS, Clark-Atlanta University, Atlanta
4. Southern University, Baton Rouge
5. University of California, Berkeley
6. Humboldt Universität zu Berlin
7. Lawrence Berkeley National Laboratory
8. Université Libre de Bruxelles
9. Vrije Universiteit Brussel
10. Chiba University
11. University of Canterbury
12. University of Maryland
13. Universität Dortmund
14. University of Gent
15. Max-Planck-Institut für Kernphysik
16. University of California, Irvine
17. University of Kansas, Lawrence
18. Imperial College London
19. Dept. of Astron., University of Wisconsin, Madison
20. Dept. of Physics, University of Wisconsin, Madison
21. University of Mainz
22. University of Mons-Hainaut,
23. Bartol Research Institute, University of Delaware
24. University of Oxford
25. Institute for Advanced Study, Princeton
26. University of Wisconsin, River Falls
27. Stockholm University
28. Dept. of Astronomy and Astrophysics, PSU
29. Dept. of Physics, PSU
30. Uppsala University
31. Utrecht University/SRON
32. University of Wuppertal
33. DESY Zeuthen

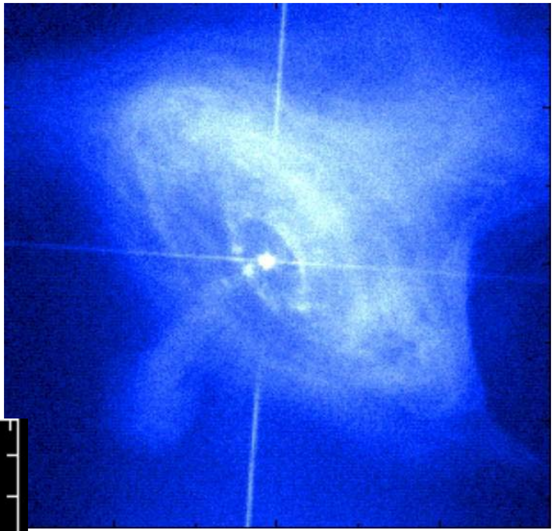
a. deceased
b. on leave of absence from Università di Bari, Dipartimento di Fisica, I-70126, Bari, Italy
c. affiliated with Dept. of Chemical and Biomedical Sciences, Kalmar University, S-39182 Kalmar, Sweden
d. affiliated with IFIC (CSIC-Universitat de València), A. C. 22085, 46071 Valencia, Spain

Multi-Wavelength Astronomy

γ-rays



x-rays



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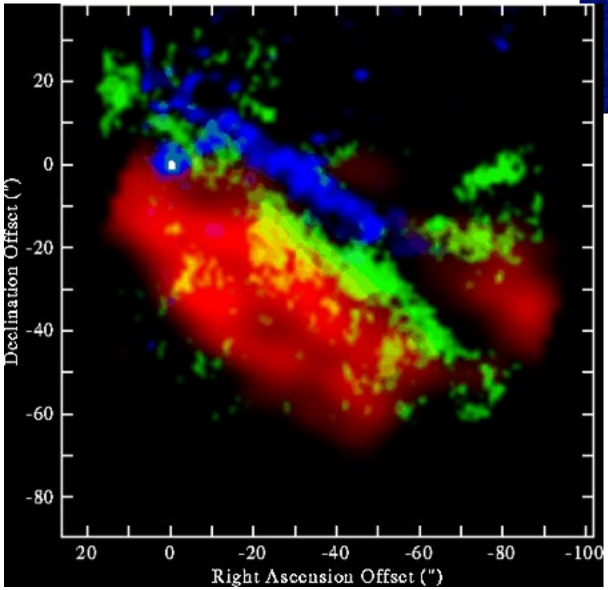
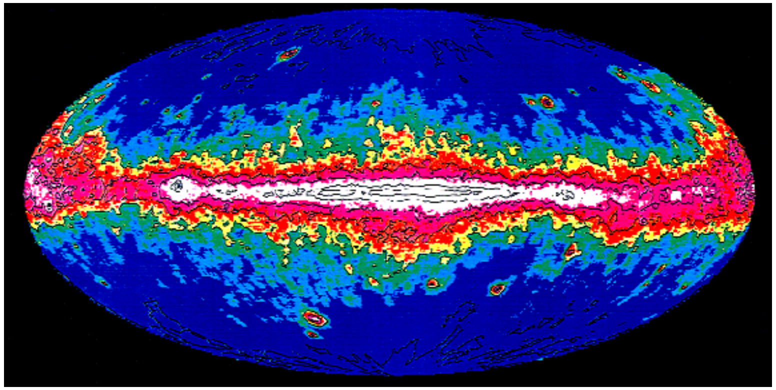


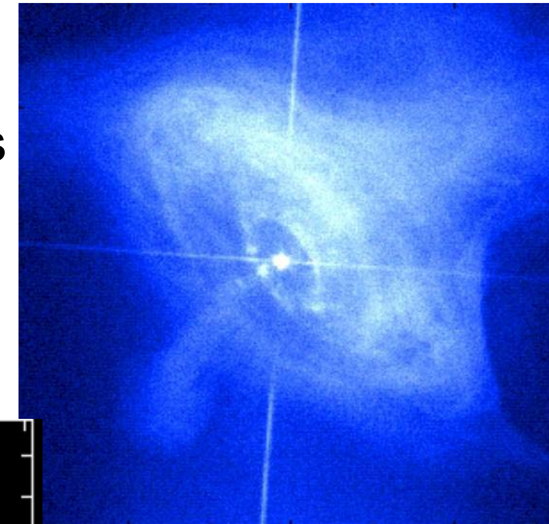
radio

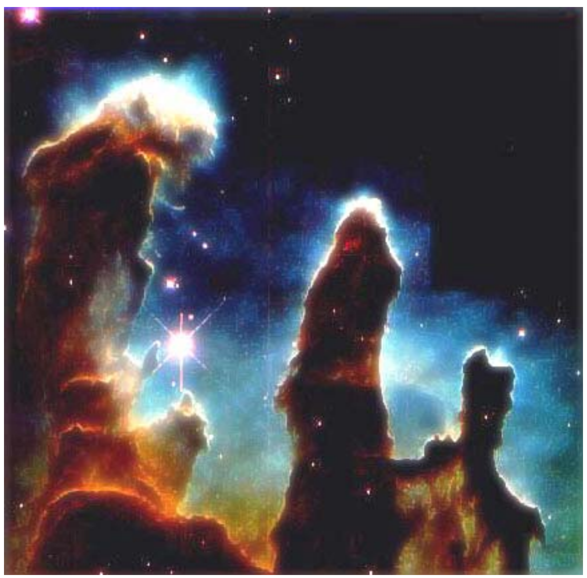
Multi-Messenger Astronomy

γ-rays



x-rays





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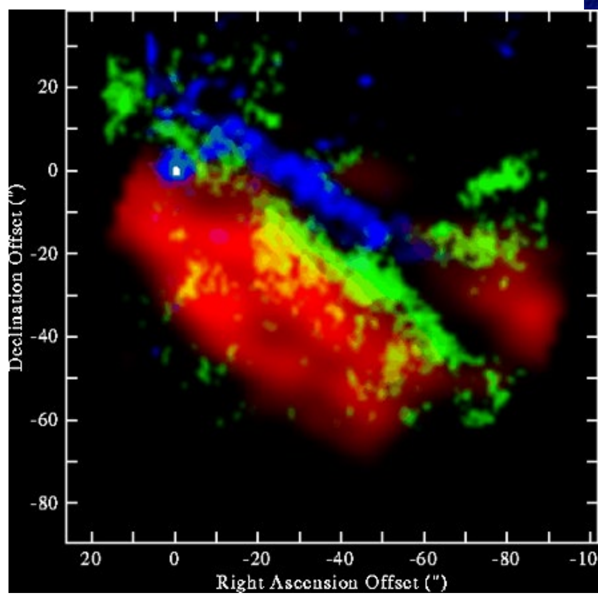
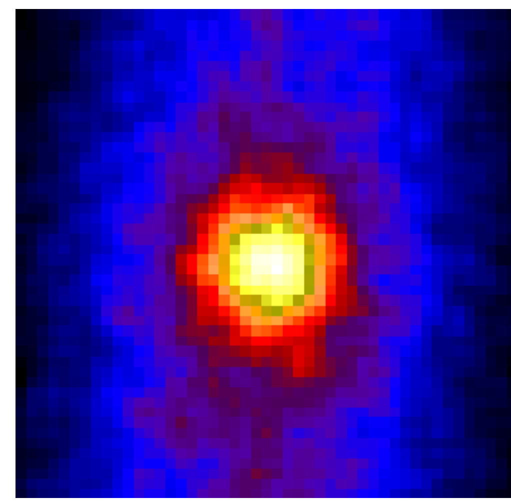


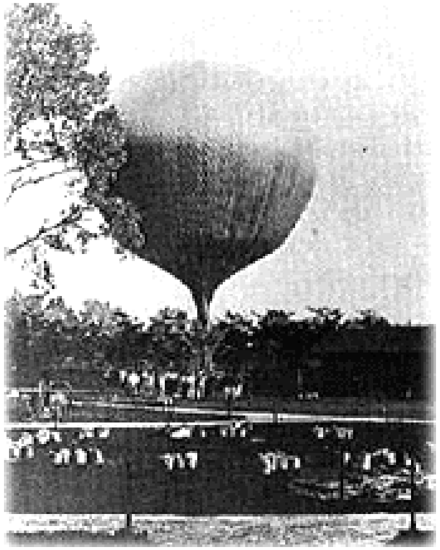
radio

Neutrinos

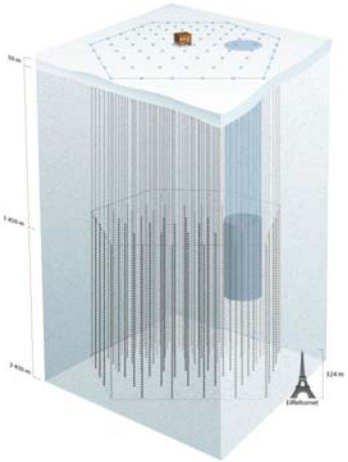


Physics Questions at the TeV Scale

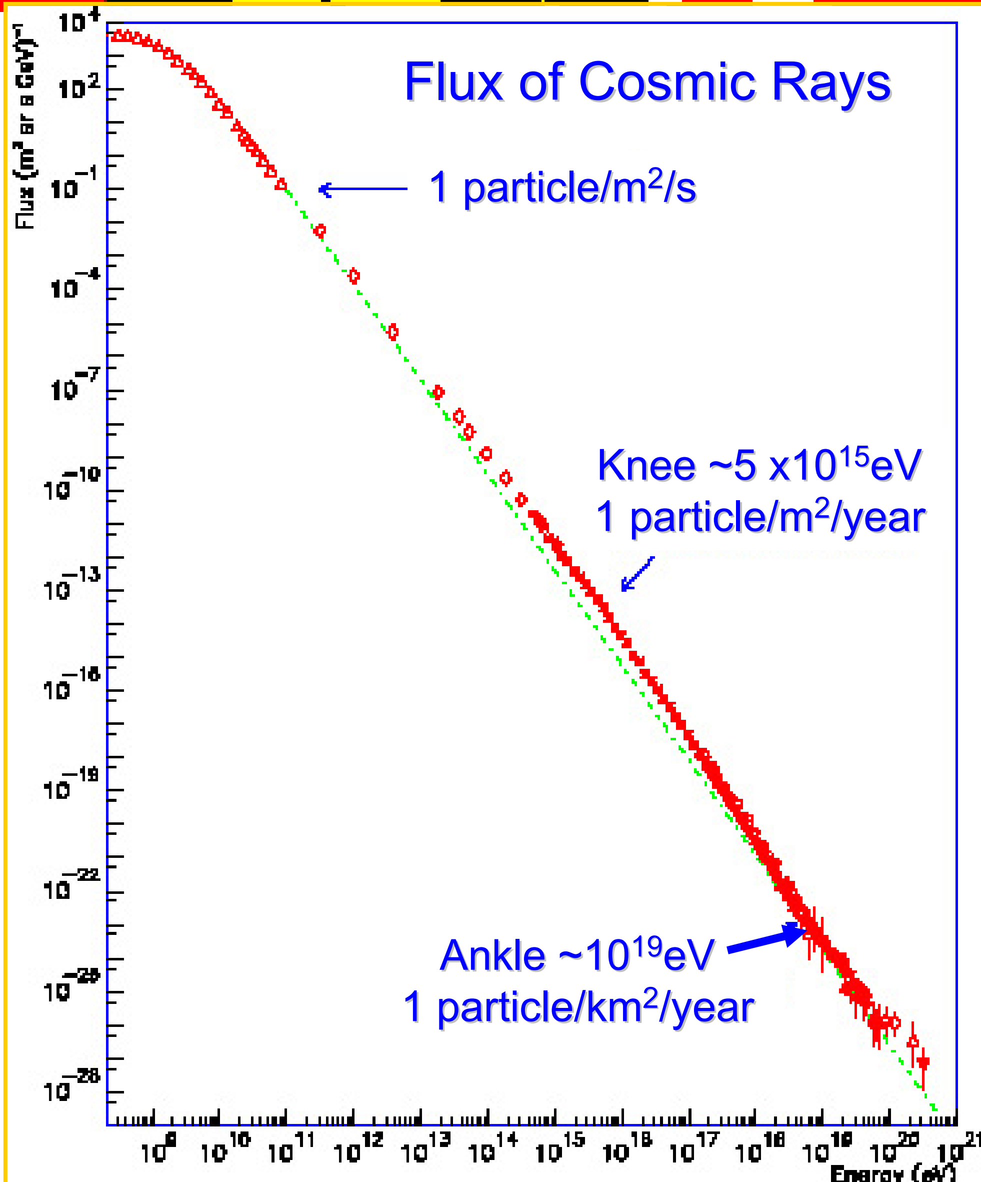
- Search for cosmic-ray accelerators
  - Active galactic nuclei
  - Supernova remnants
  - Gamma-ray bursts
- Dark Matter
  - Supersymmetry / WIMPs, exotic particles
- Neutrino / particle-physics
  - UHE cross-section measurements
  - Charm physics
  - Neutrino oscillations
  - Tests Lorentz Invariance – gamma of TeV-scale neutrinos way beyond reach of other techniques.
- Supernova neutrinos (MeV-scale)



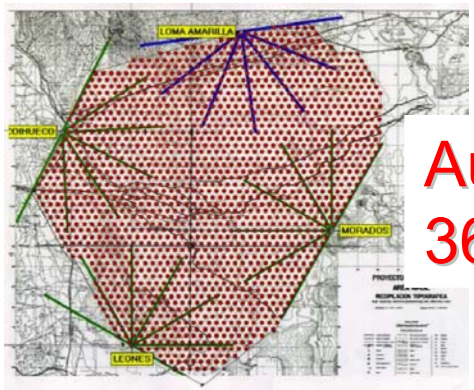
Victor Hess in 1912



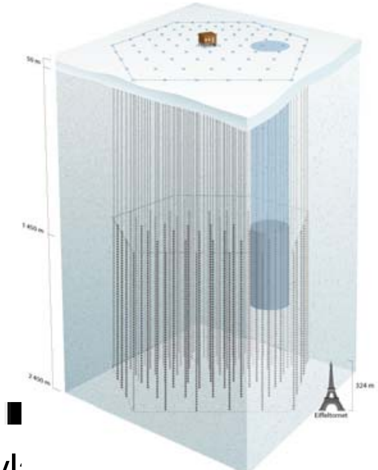
Origin of Cosmic Rays



At the highest energies, the extraordinary small flux requires enormous detectors!



Auger – 3600 km²

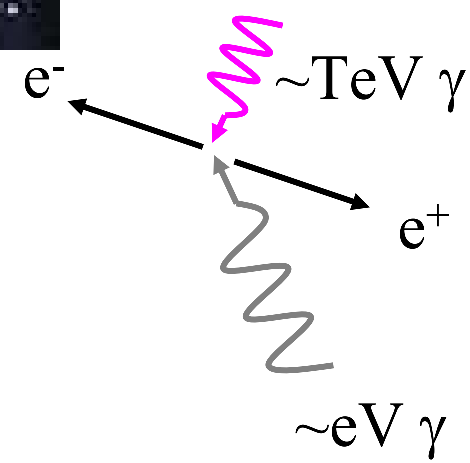


IceCube 1 km³

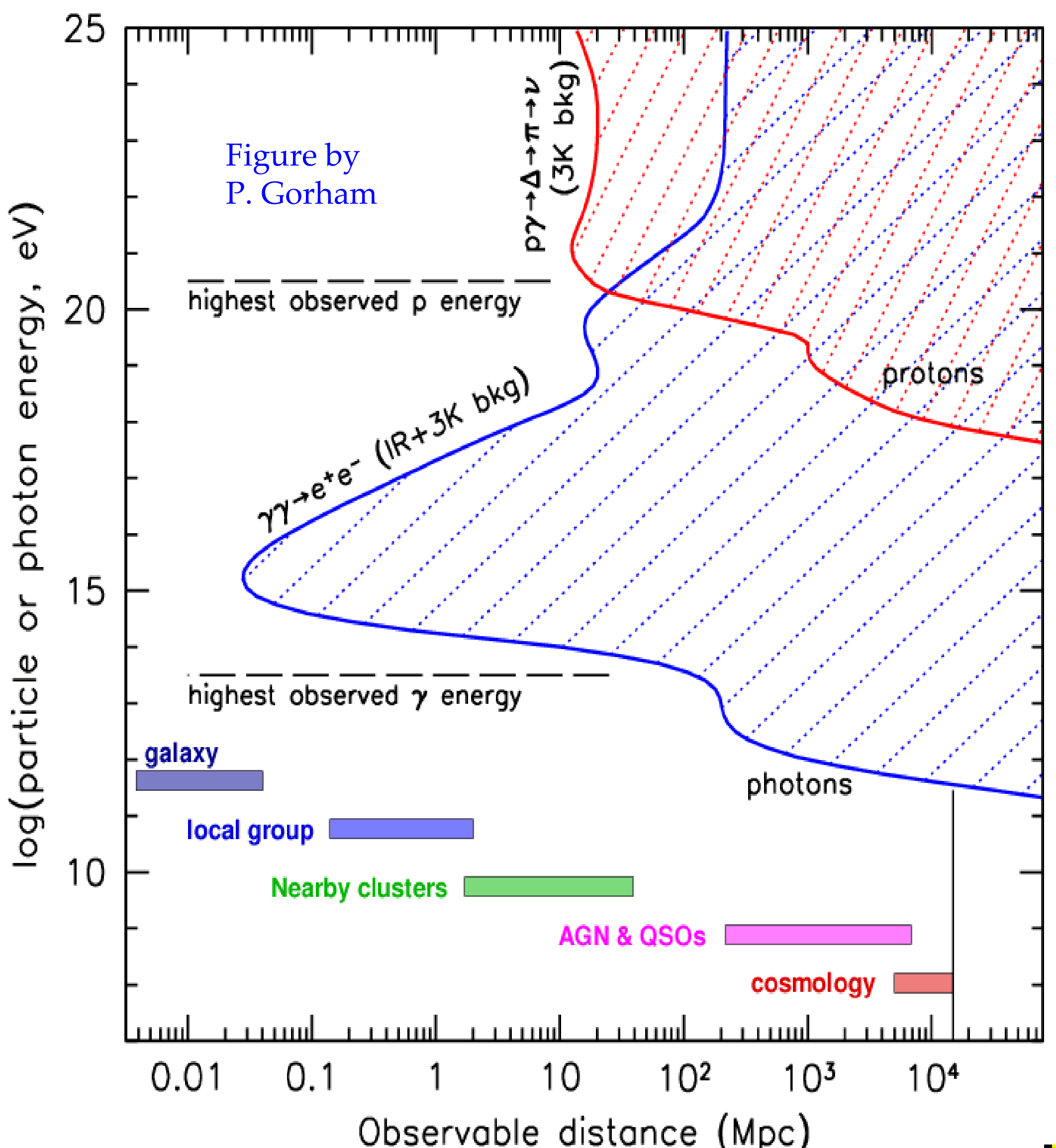
Why not Protons or Photons?

- Protons are bent in the magnetic fields of our galaxy and local cluster
  - Energy of $>10^{19}$eV needed to point back to even galactic sources
  - Above a few 10^{19}eV GZK cutoff limits their range too

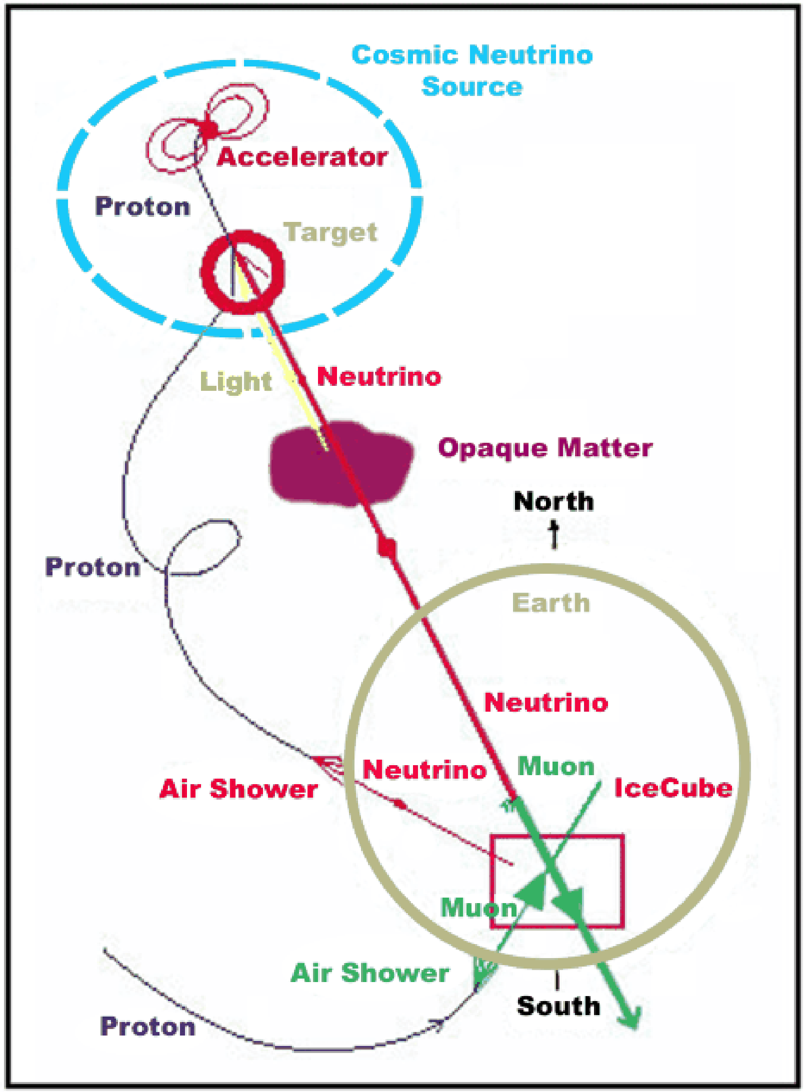
- Photons pair produce
  - Above ~100 GeV on IR
  - Above ~100 TeV on CMB

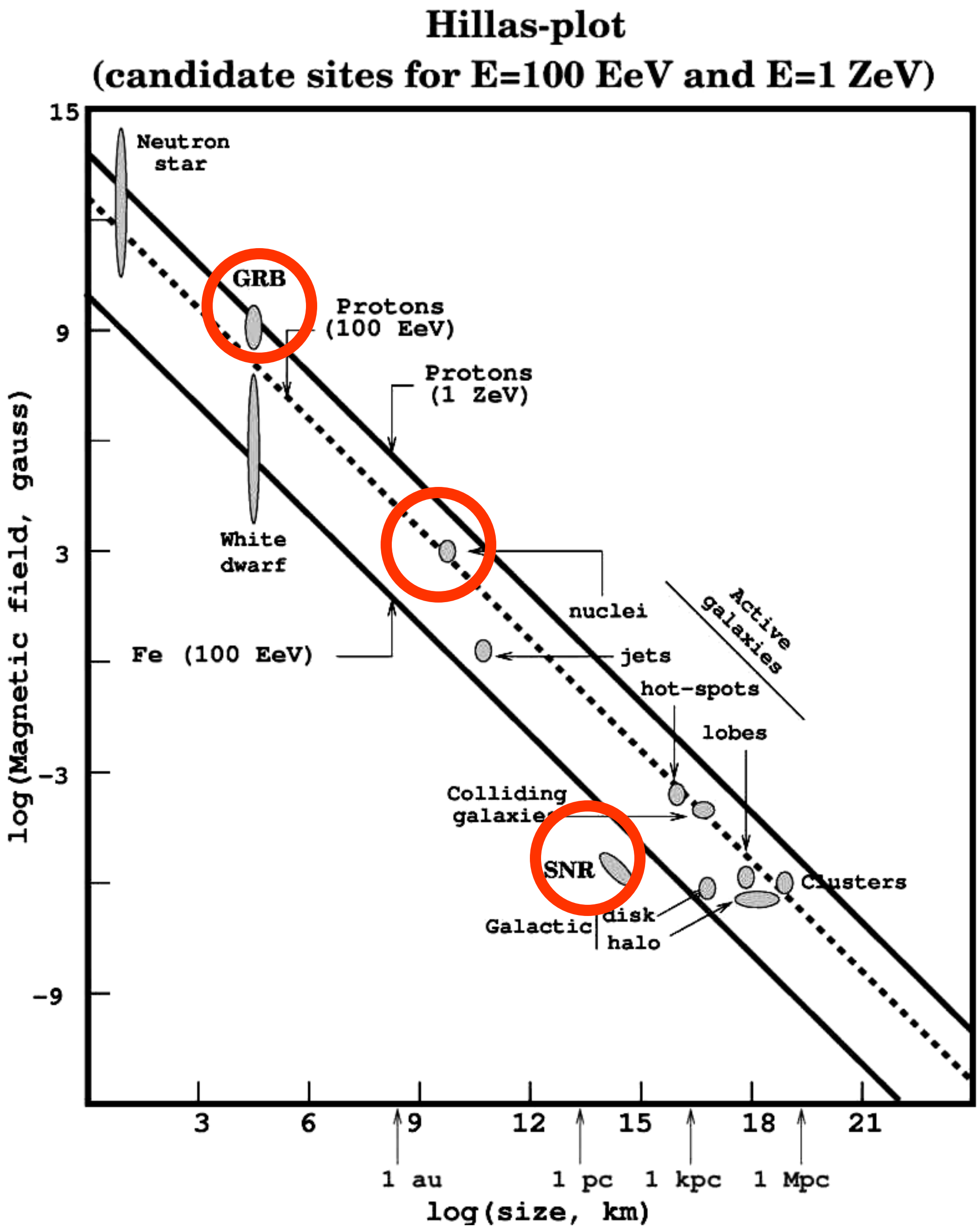


The Visible Universe



A Neutrino Telescope

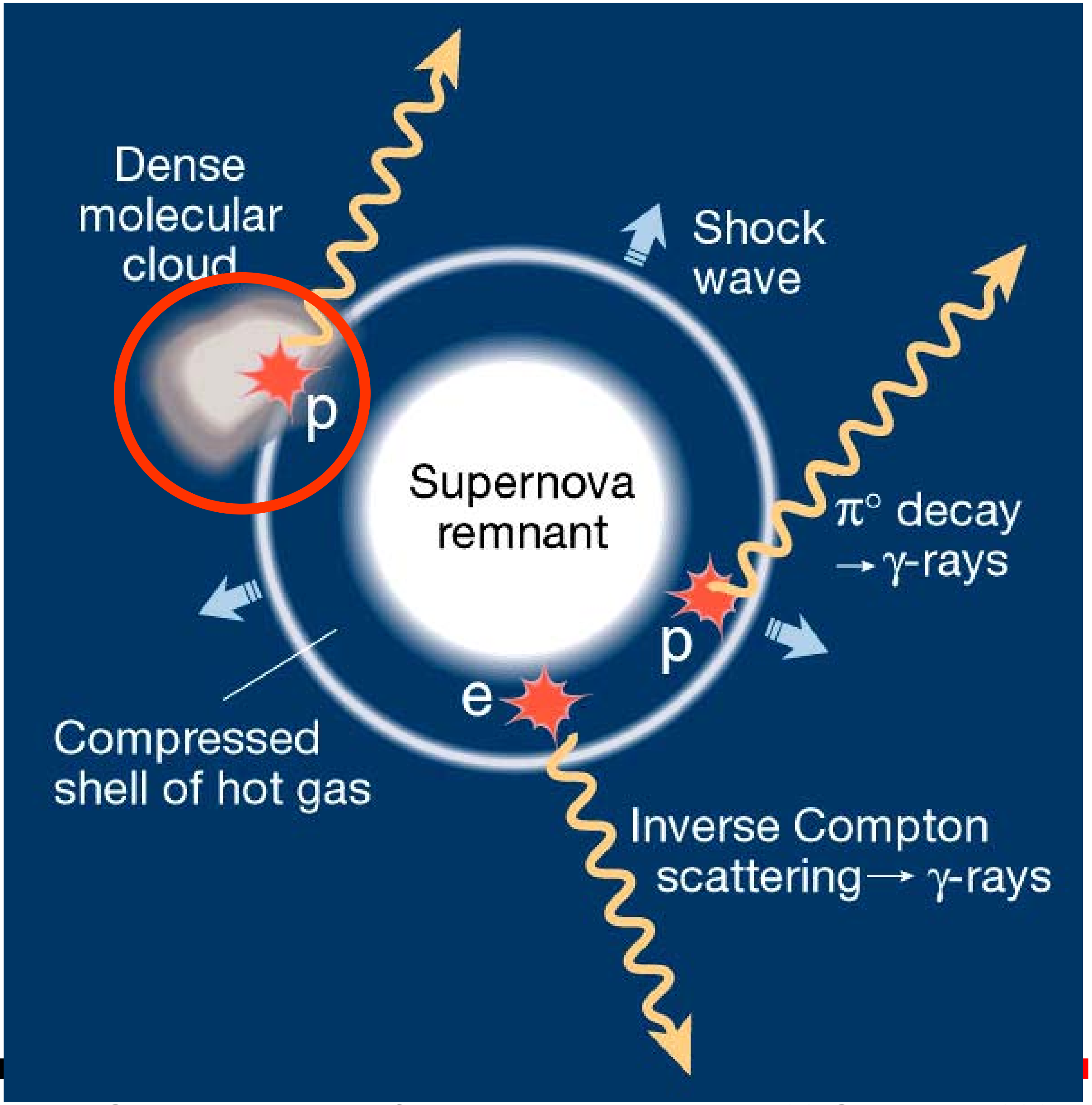




Potential sources of UHE Cosmic Rays

Magnetic field must be strong enough over large enough volume

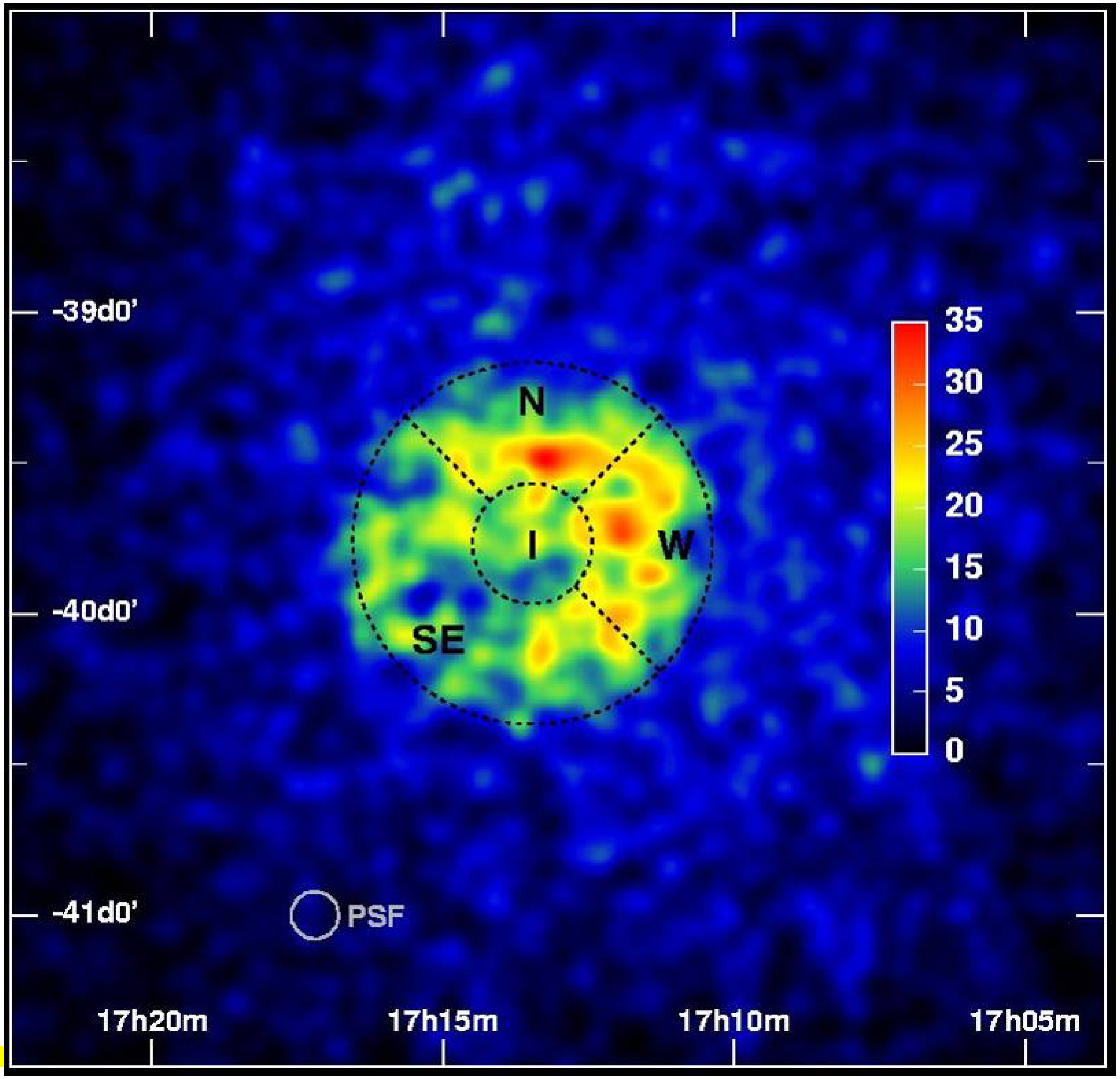
SNRs


Dense
molecular
cloud
p
Shock
wave
Supernova
remnant
π° decay
$\rightarrow \gamma$-rays
p
e
Compressed
shell of hot gas
Inverse Compton
scattering $\rightarrow \gamma$-rays

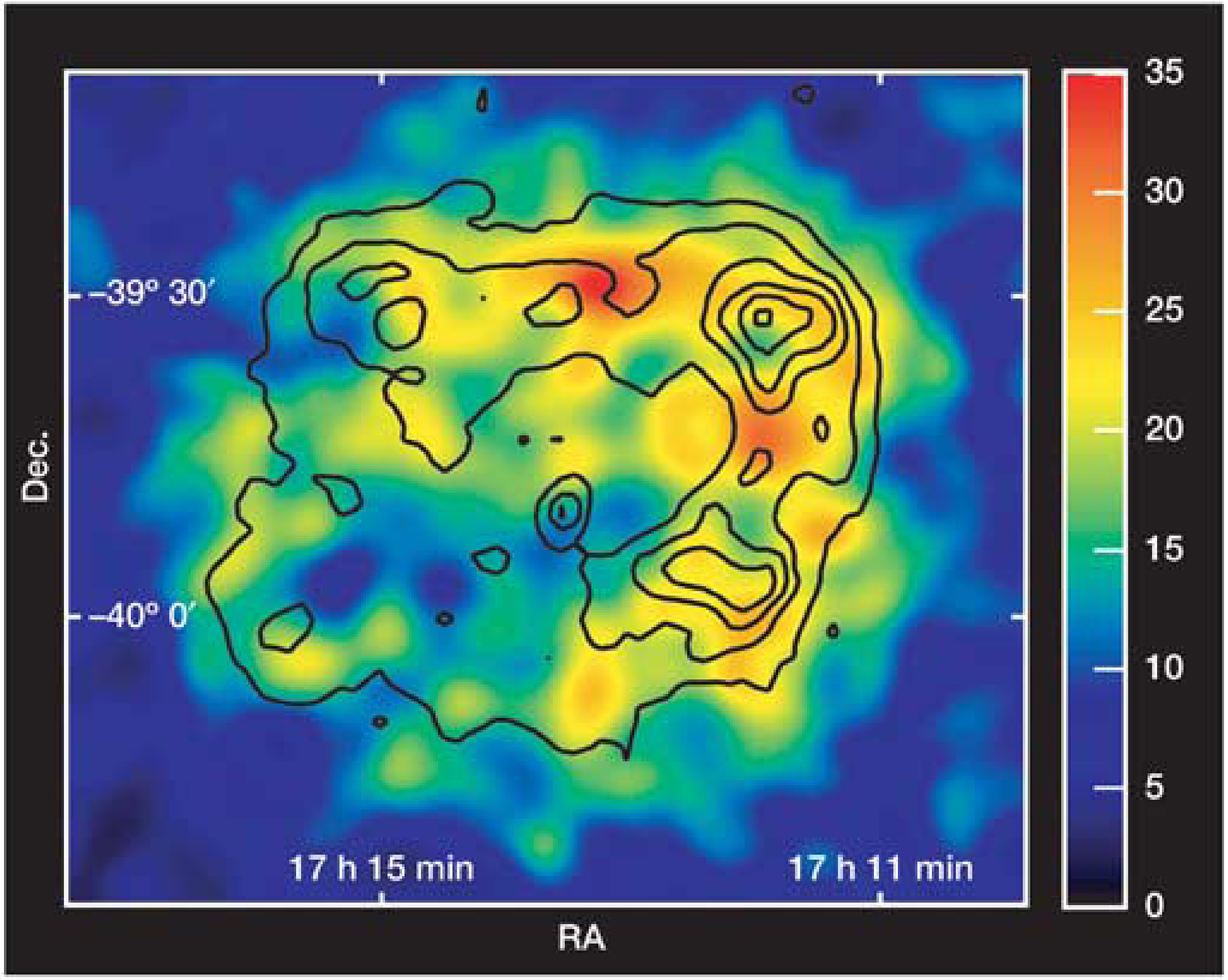
HESS: RXJ1713

First resolved
TeV γ-ray image of a Shell type SNR
(Resolution ~10 arcmin)

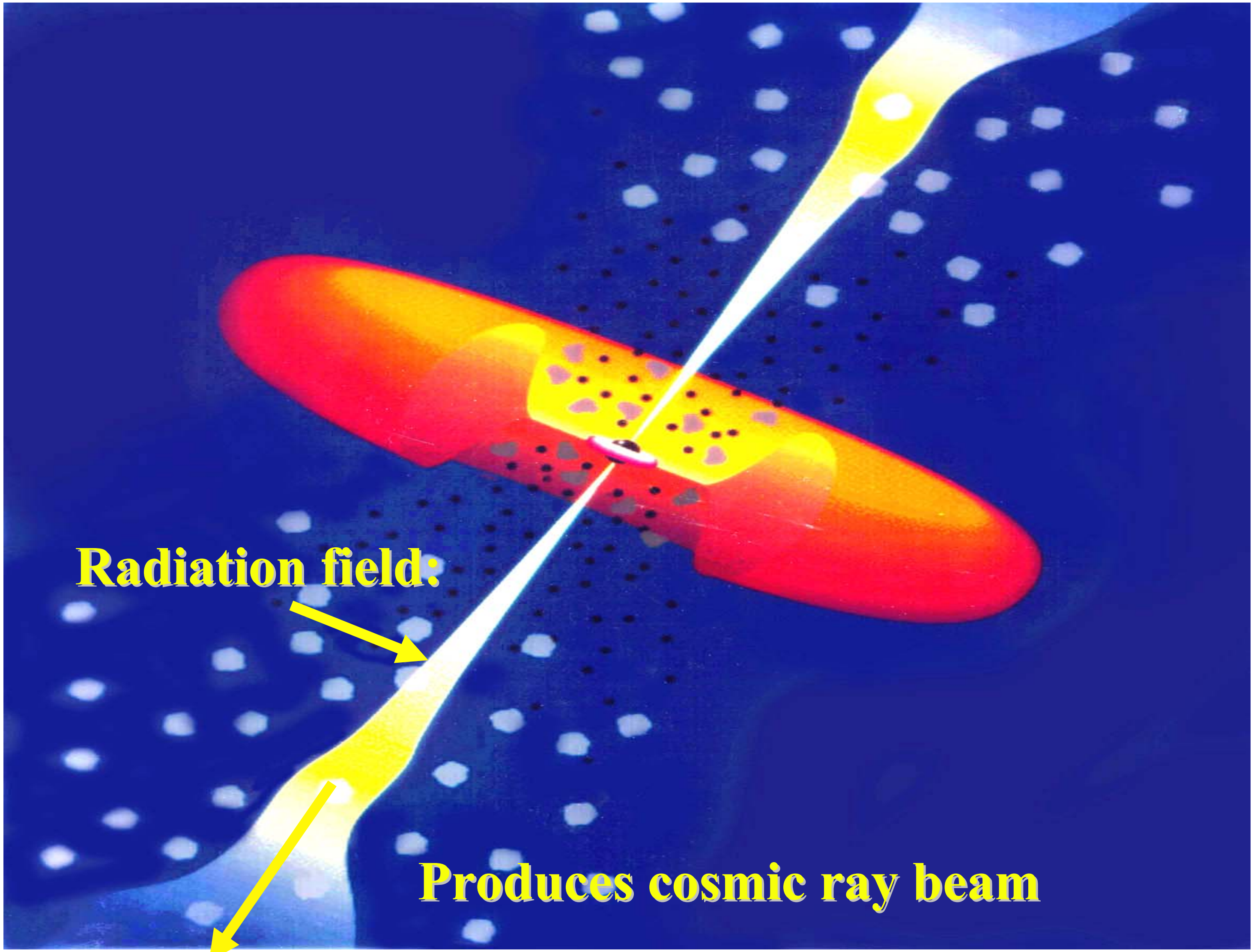
Acceleration source of Cosmic Rays, but is it evidence of Protons?



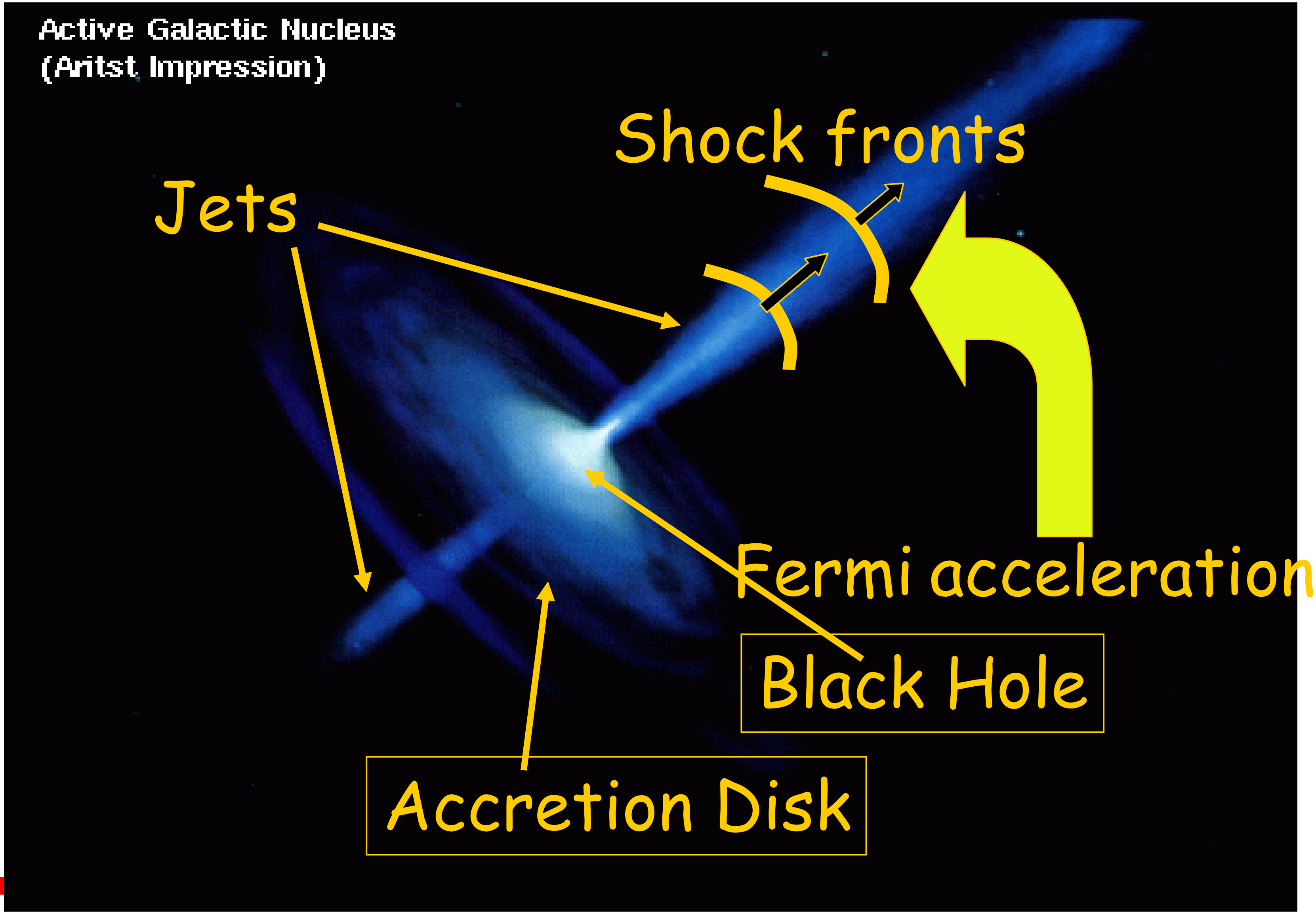
HESS: RXJ1713 – Molecular Clouds



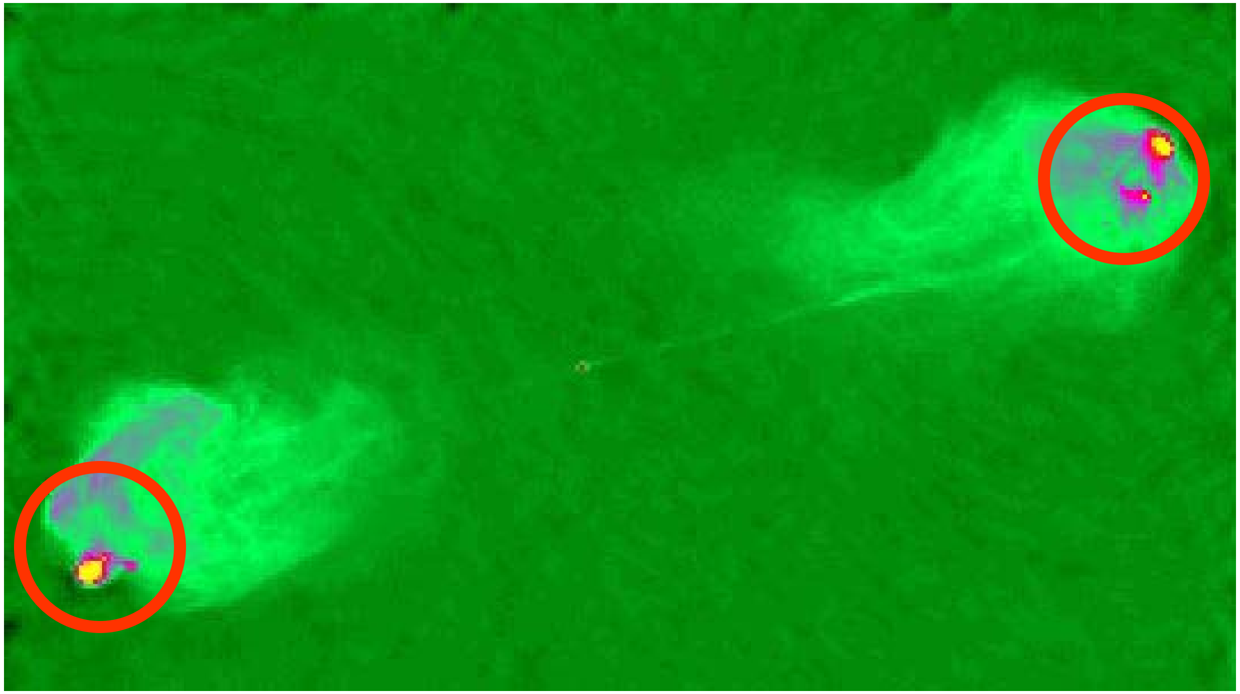
Active Galactic Nuclei



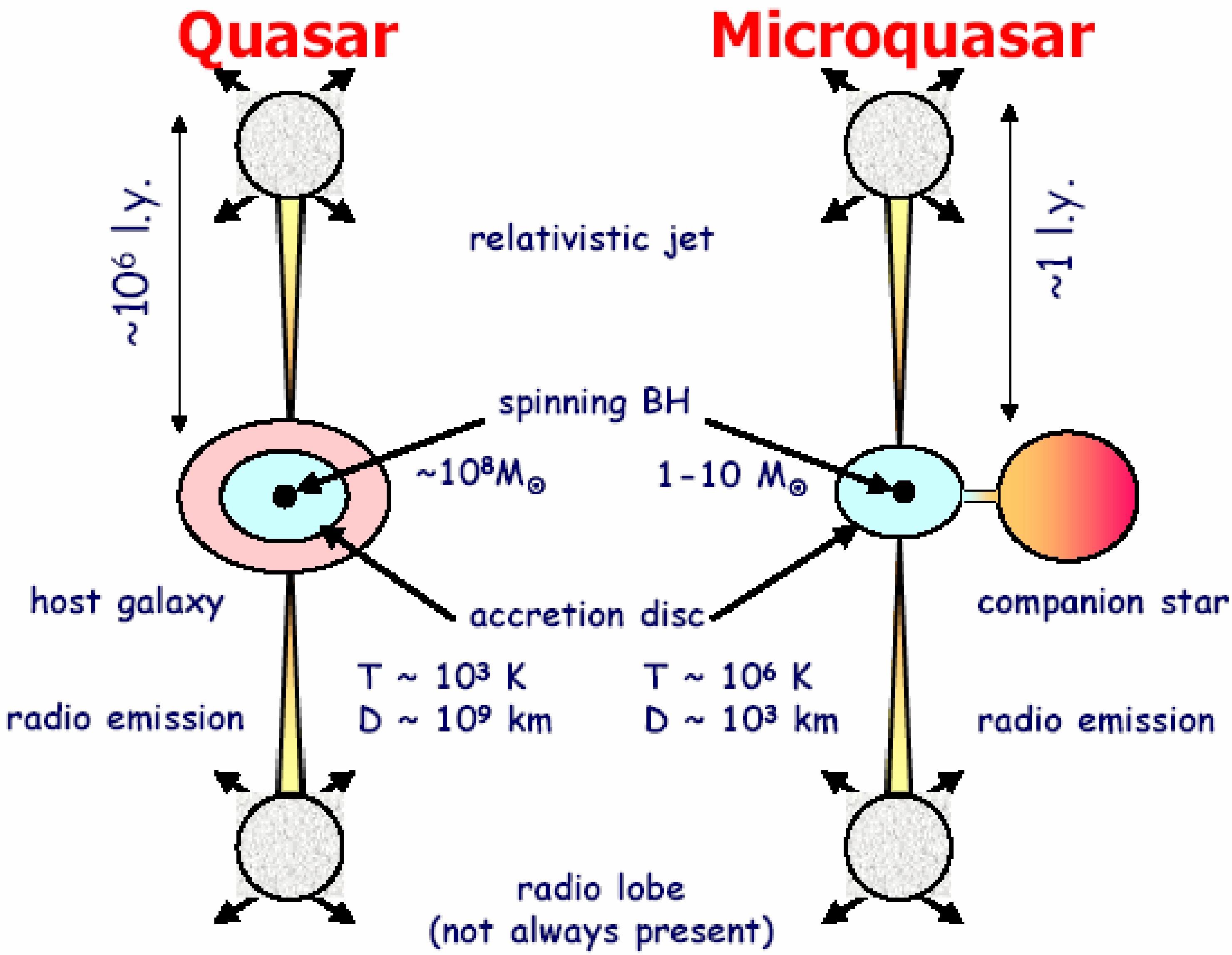
Active Galactic Nuclei (AGN)



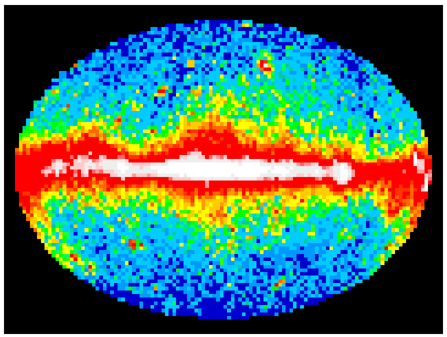
VLA image of Cygnus A

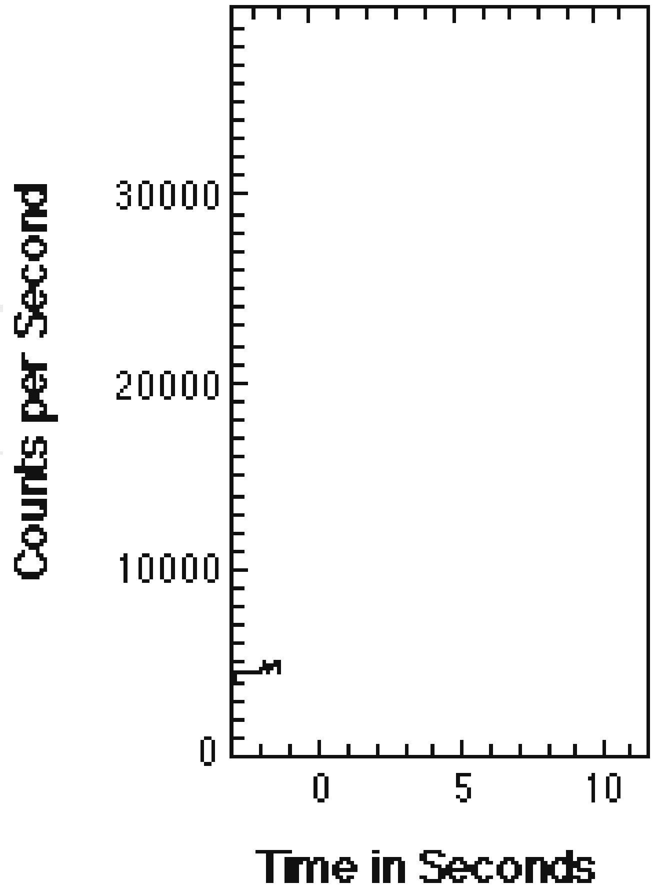


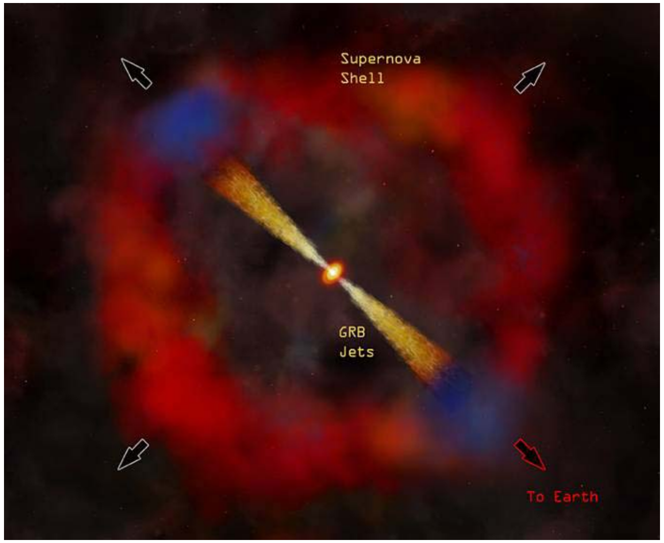
Galactic Microquasars

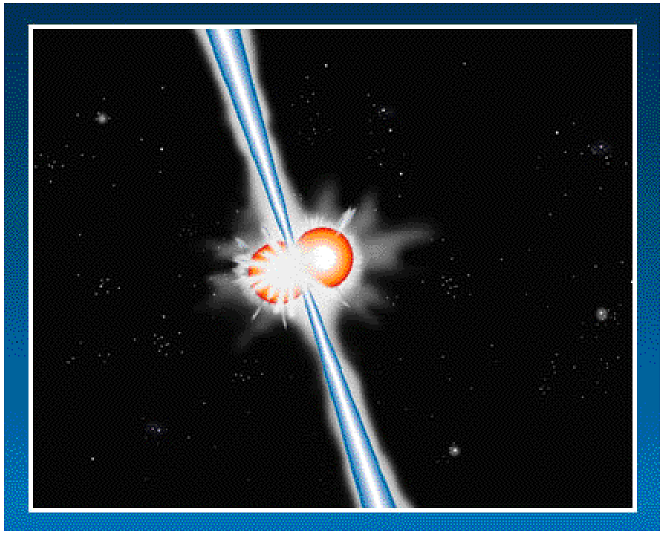


GRBs



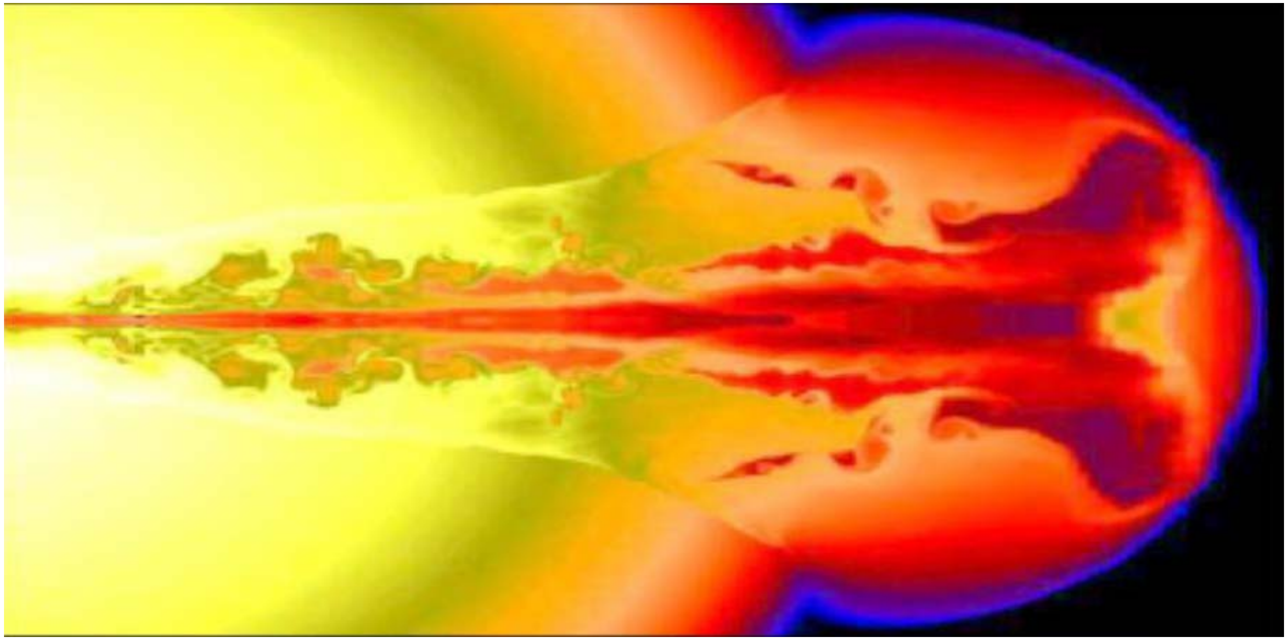

Counts per Second
30000
20000
10000
0
0
5
10
Time in Seconds


Supernova Shell
GRB Jets
To Earth

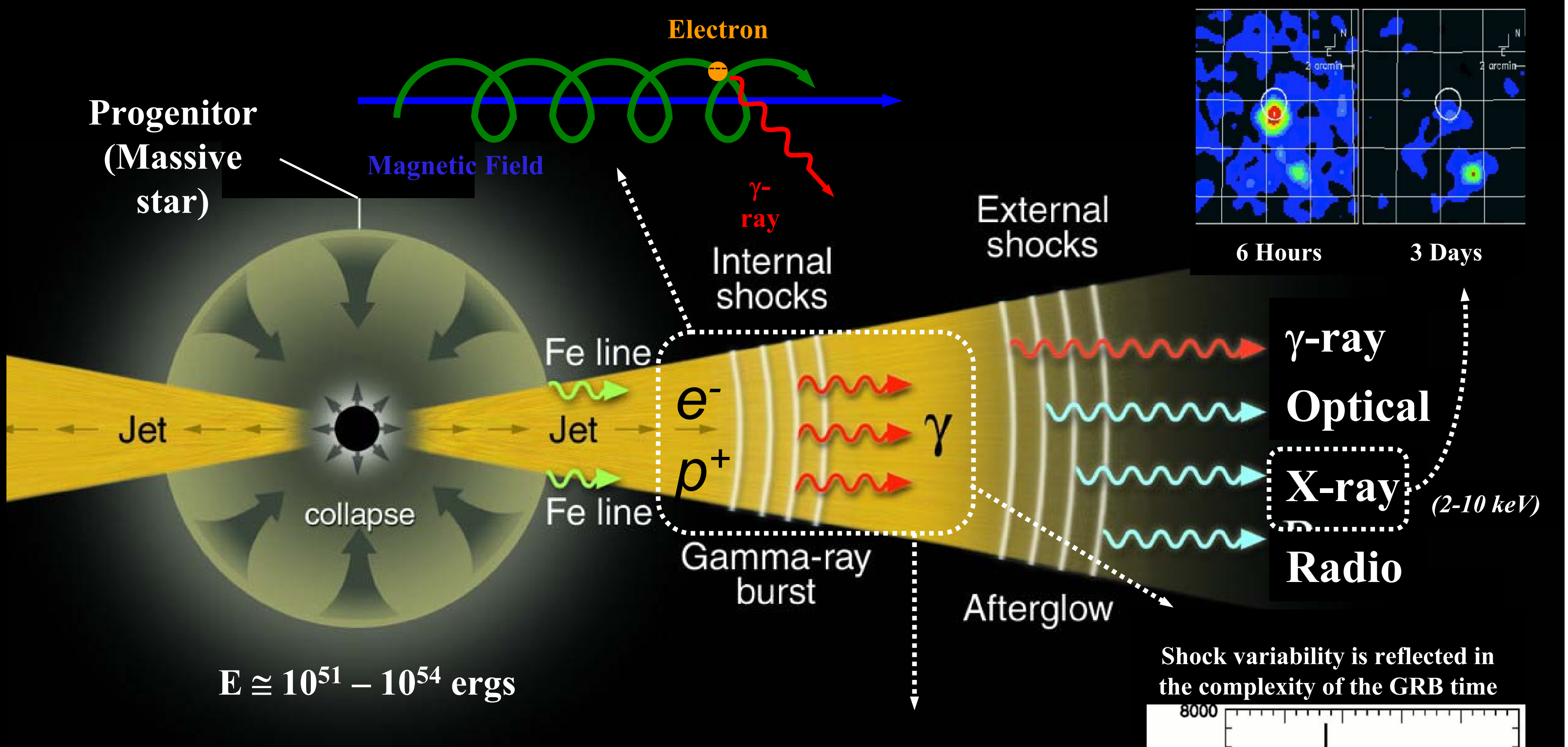


GRBs

Shocks: *external* collisions with interstellar material or *internal* collisions when slower material is overtaken by faster in the fireball.



Fireball Phenomenology & The Gamma-Ray Burst (GRB) Neutrino Connection



$$p^+ + \gamma \rightarrow \Delta^+ \rightarrow (n) + \pi^+ \rightarrow \nu_\mu + \mu^+ \rightarrow \nu_\mu + e^+ + \nu_e + \bar{\nu}_\mu$$

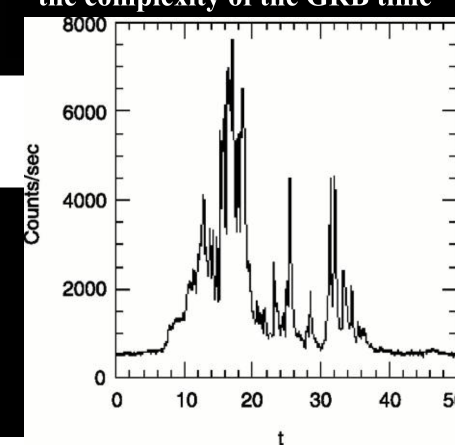
Meszaros, P

$R < 10^8$ cm

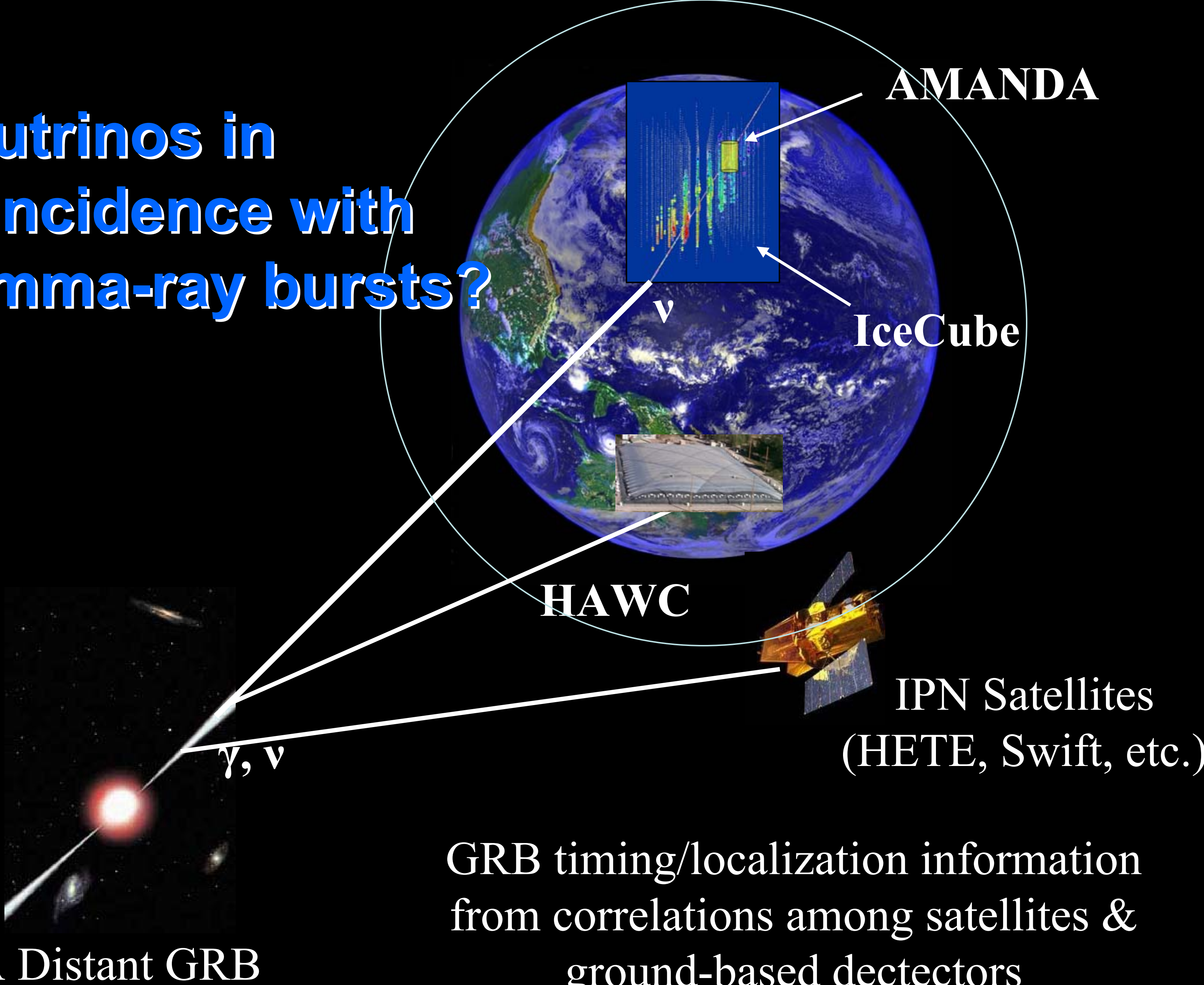
$R \le 10^{14}$ cm, $T \cong 3 \times 10^3$ seconds

$R \le 10^{18}$ cm, $T \cong 3 \times 10^{16}$ seconds

Shock variability is reflected in the complexity of the GRB time



Neutrinos in coincidence with gamma-ray bursts?



GRB timing/localization information from correlations among satellites & ground-based dectectors

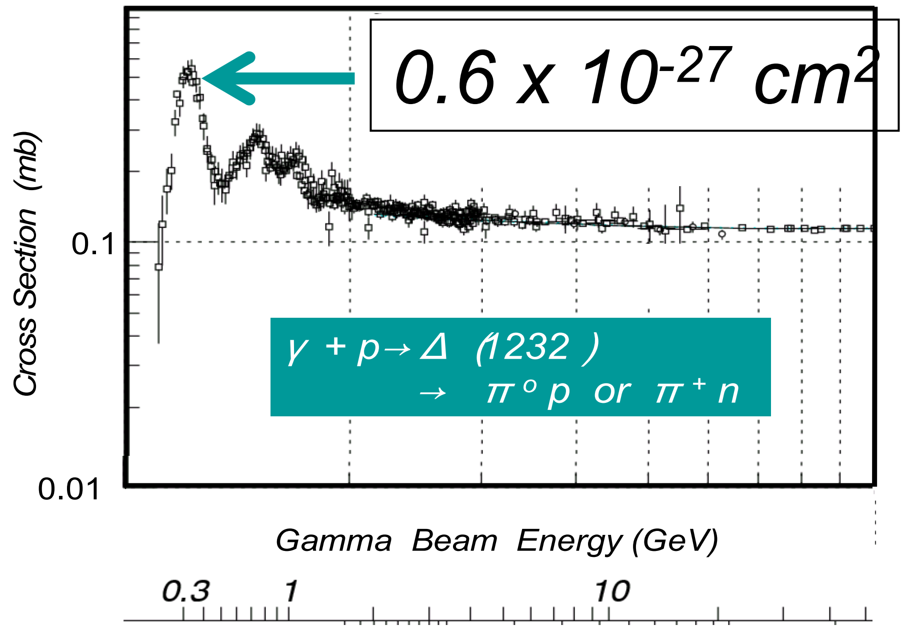
GZK

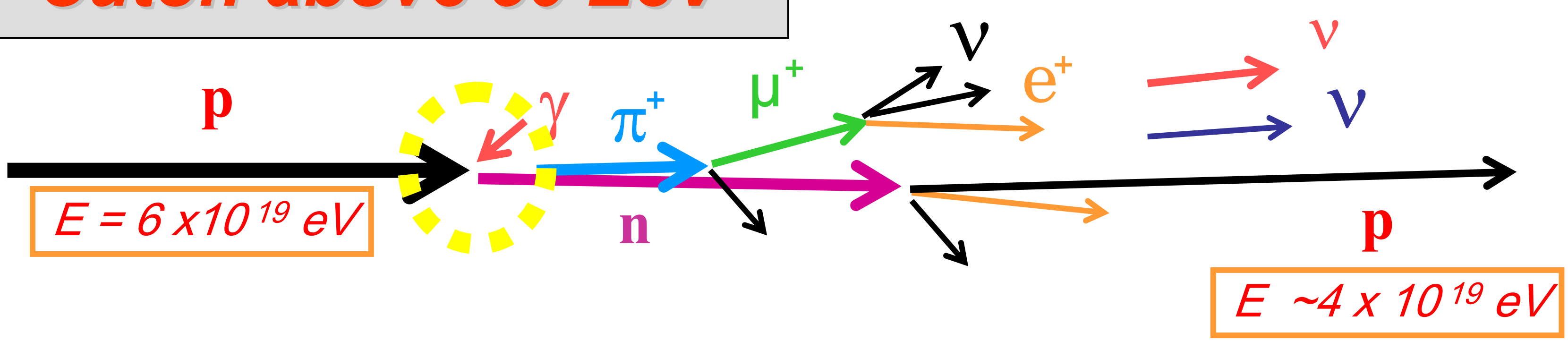
$$p + \gamma_{CMB} \longrightarrow \pi^{+} + n$$

$$\lambda = (n_{cmb}\ \sigma_{p+\gamma})^{-1}$$

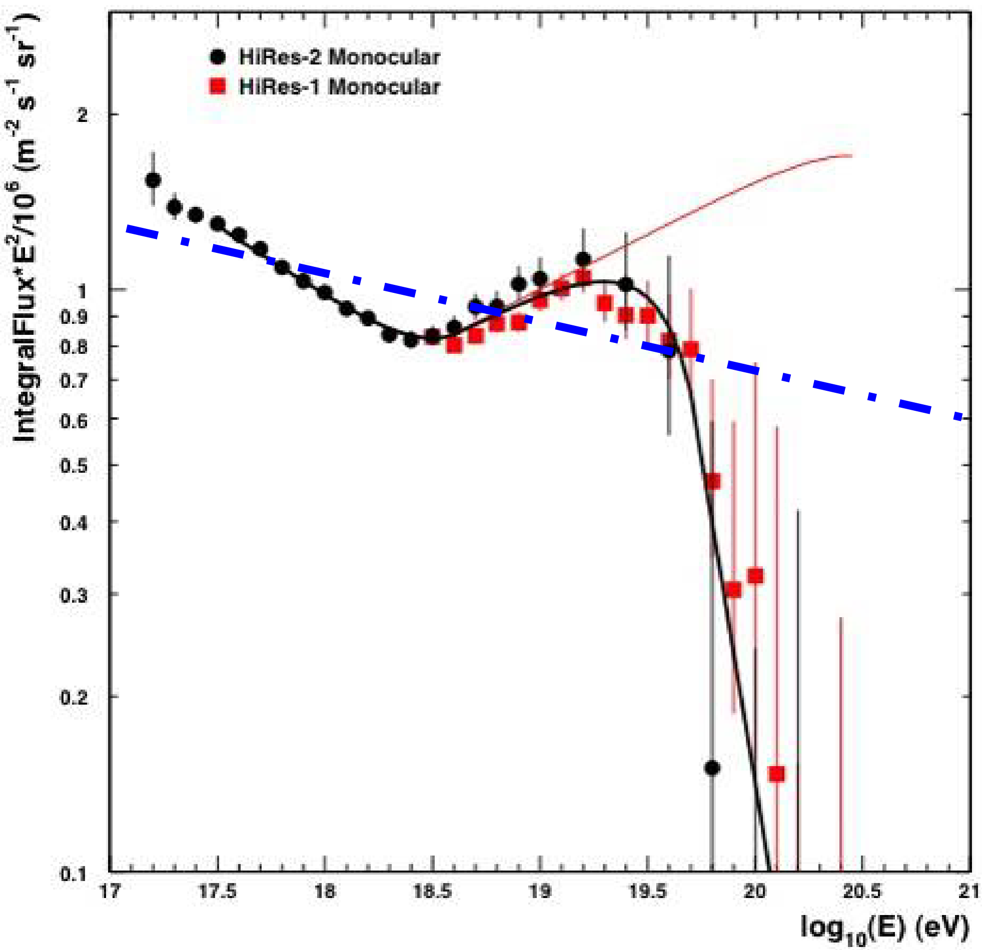
$$\lambda = 10\ Mpc$$

Cutoff above 50 EeV





GZK



Cosmogenic neutrinos are guaranteed if primaries are nucleons.

May be much larger fluxes, for some models, such as topological defects

Flavor Ratios

- The ratio of flavors at the source is expected to be

$$0:2:1 = \nu_\tau : \nu_\mu : \nu_e$$

- Since the distance to the source is >> than the oscillation length – any admixture at the source should wind up:

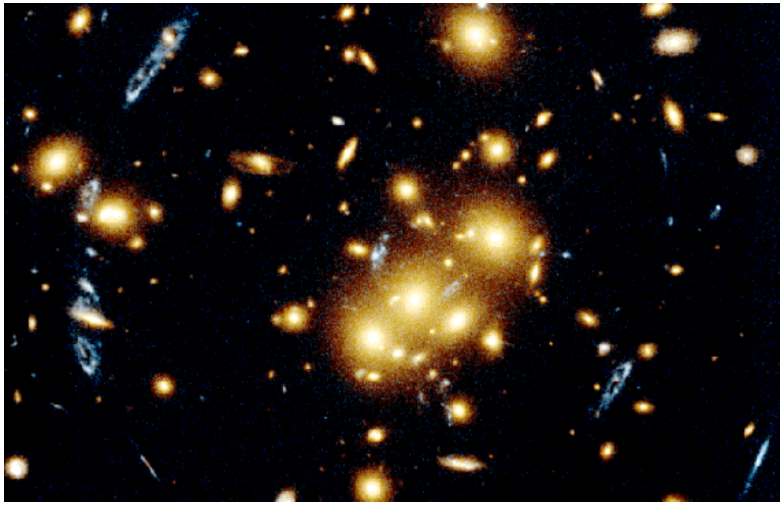
$$1:1:1 = \nu_\tau : \nu_\mu : \nu_e$$

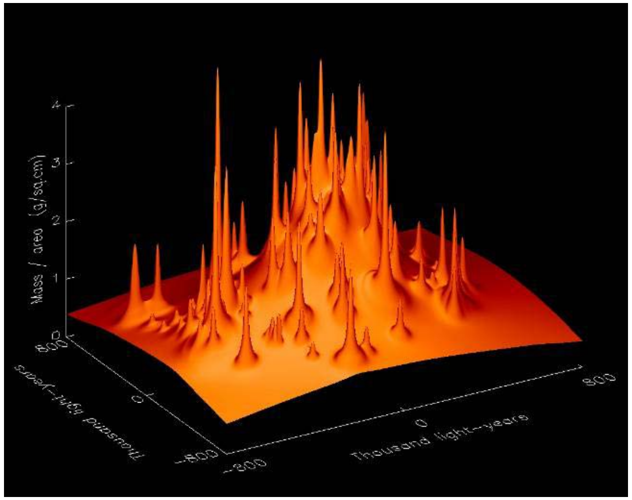
when arriving at earth

- What if that isn't true?

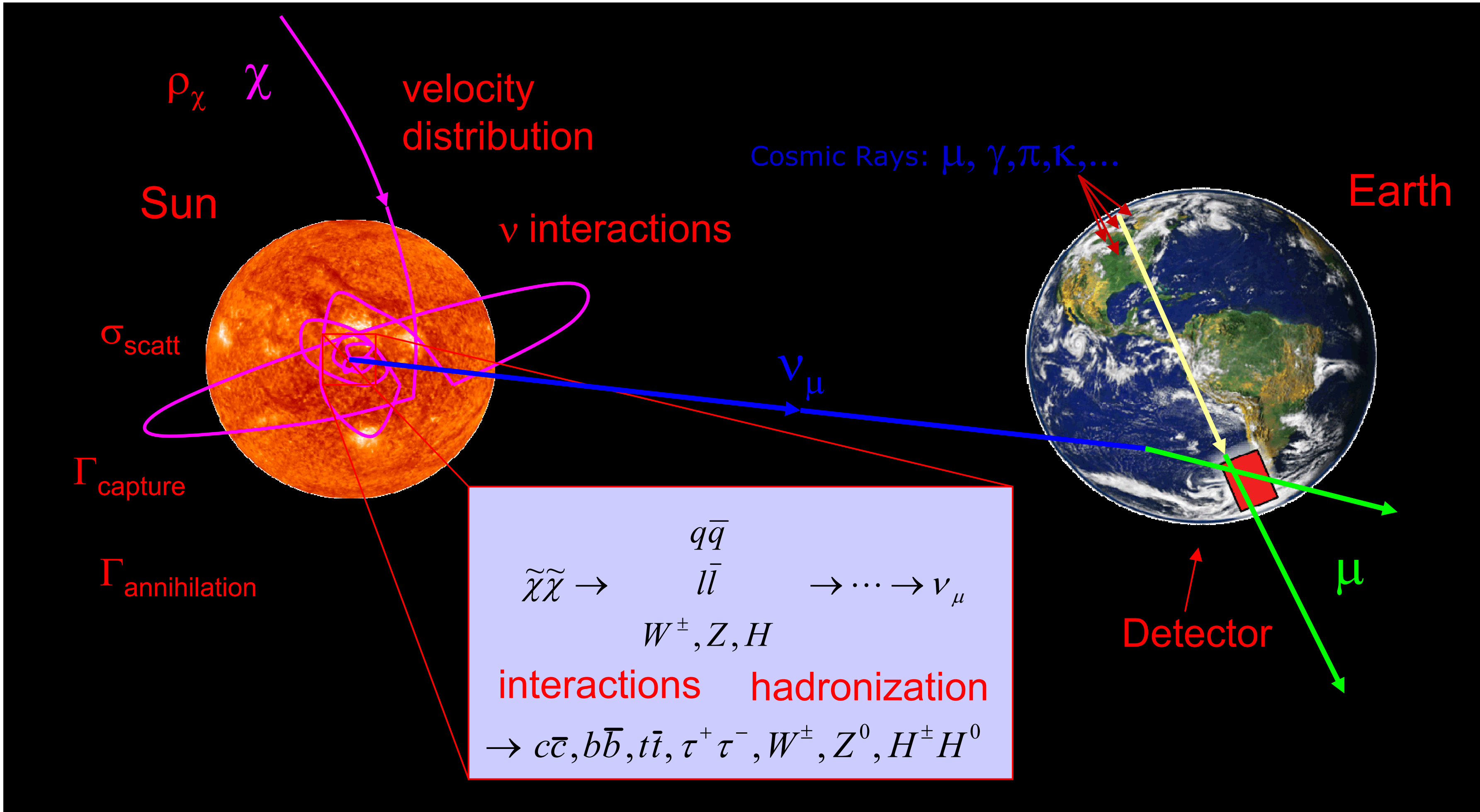
What About Dark Matter?

- ~85% of the matter in the Universe is Dark Matter
  - At most a few % of the matter is baryons
  - Most people believe that the lightest SUSY particle is a stable neutralino and is probably the dark matter
  - These are weakly interacting and heavy
  - Evidence of clustering





Wimps



$$\tilde{\chi}\tilde{\chi} \to \begin{matrix} q\bar{q} \\ l\bar{l} \\ W^{\pm}, Z, H \end{matrix} \to \cdots \to \nu_\mu$$

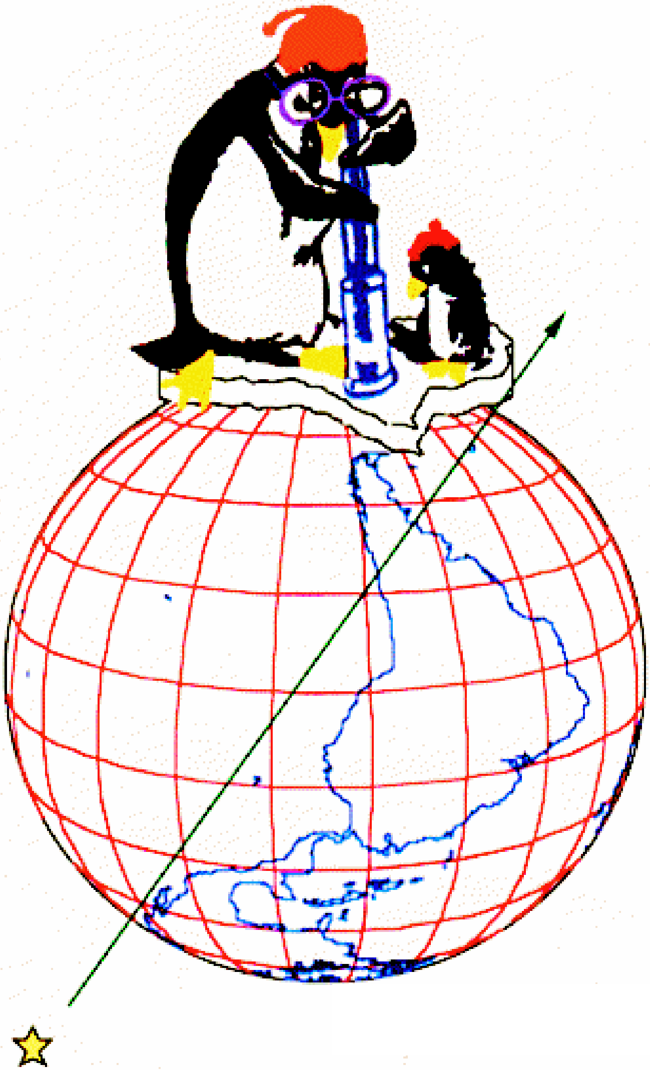
interactions hadronization

$$\to c\bar{c}, b\bar{b}, t\bar{t}, \tau^+\tau^-, W^{\pm}, Z^0, H^{\pm}H^0$$

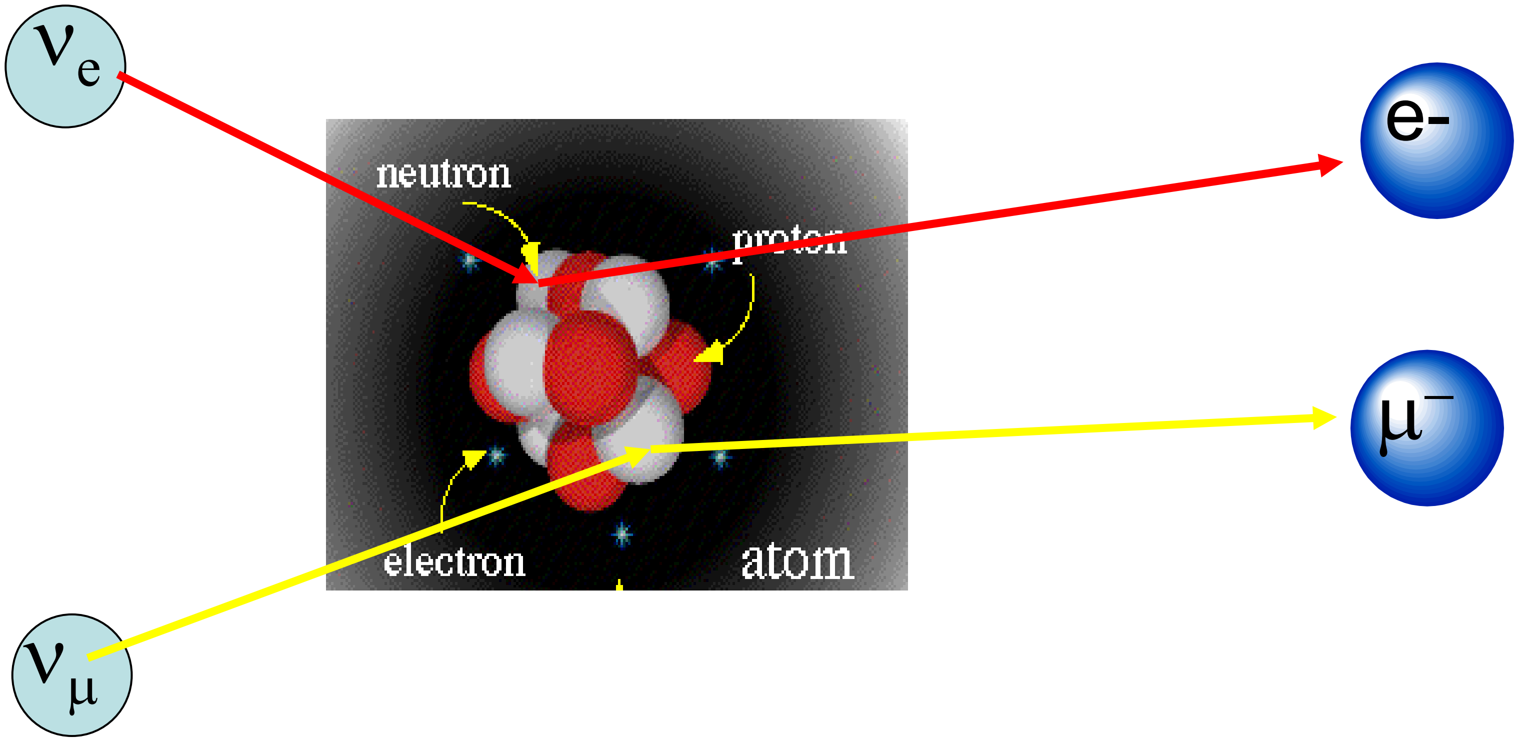
The Sun sinks maximally 23° below the horizon at the south pole

Also look for Wimps trapped in the gravity well of the earth.

How Do We Detect Neutrinos?



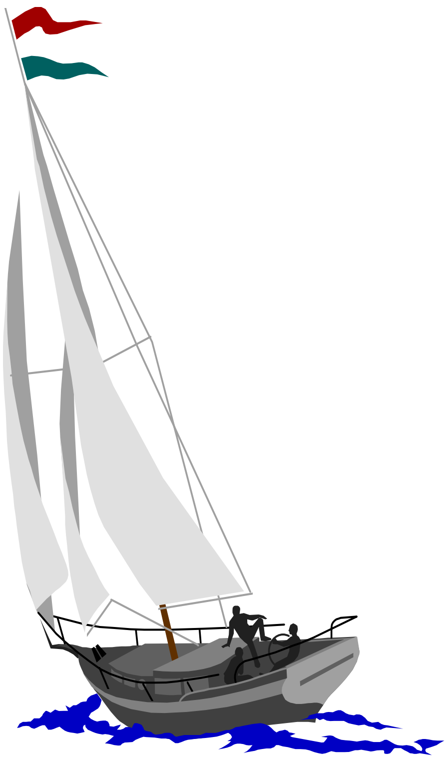
How do we see neutrinos?



Cherenkov Radiation

Boat moves through water faster than wave speed.

Bow wave (wake)



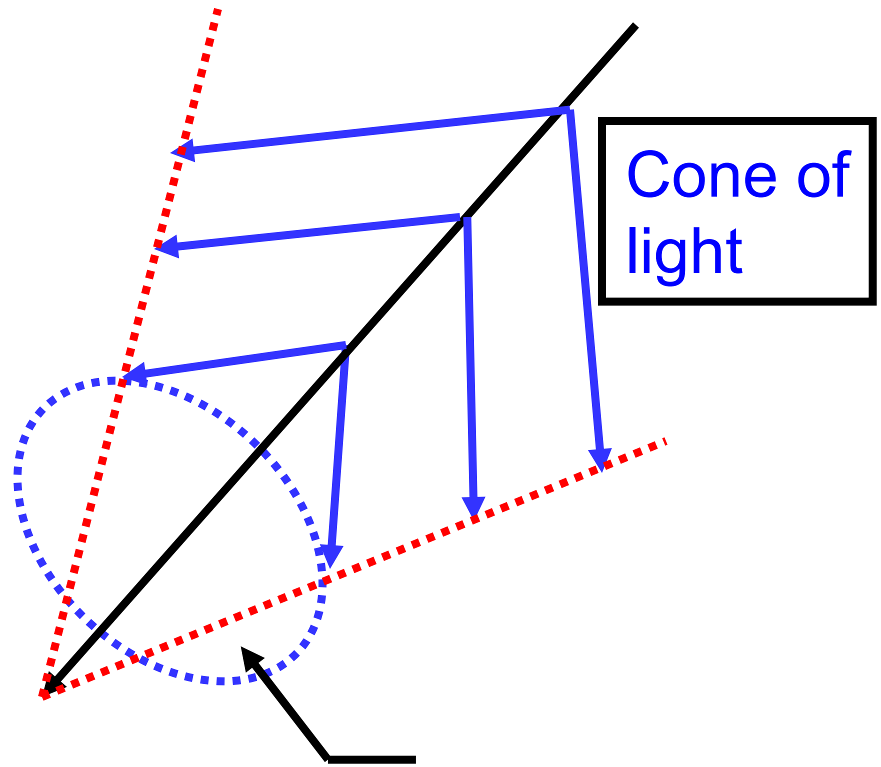
Cherenkov Radiation

Aircraft moves through air faster than speed of sound.

Sonic Boom

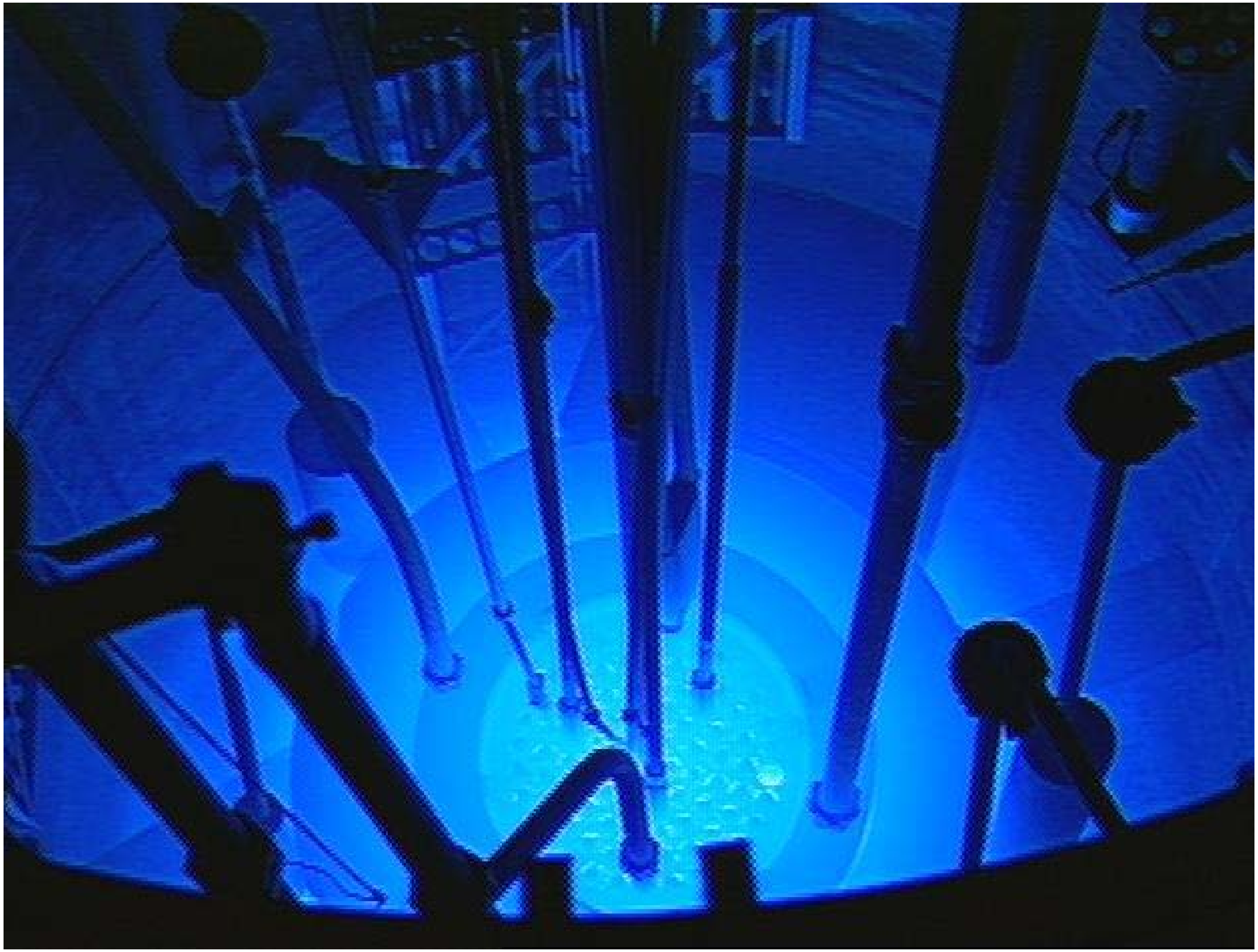
Cherenkov Radiation

When a charged particle moves through transparent media faster than speed of light in that media.

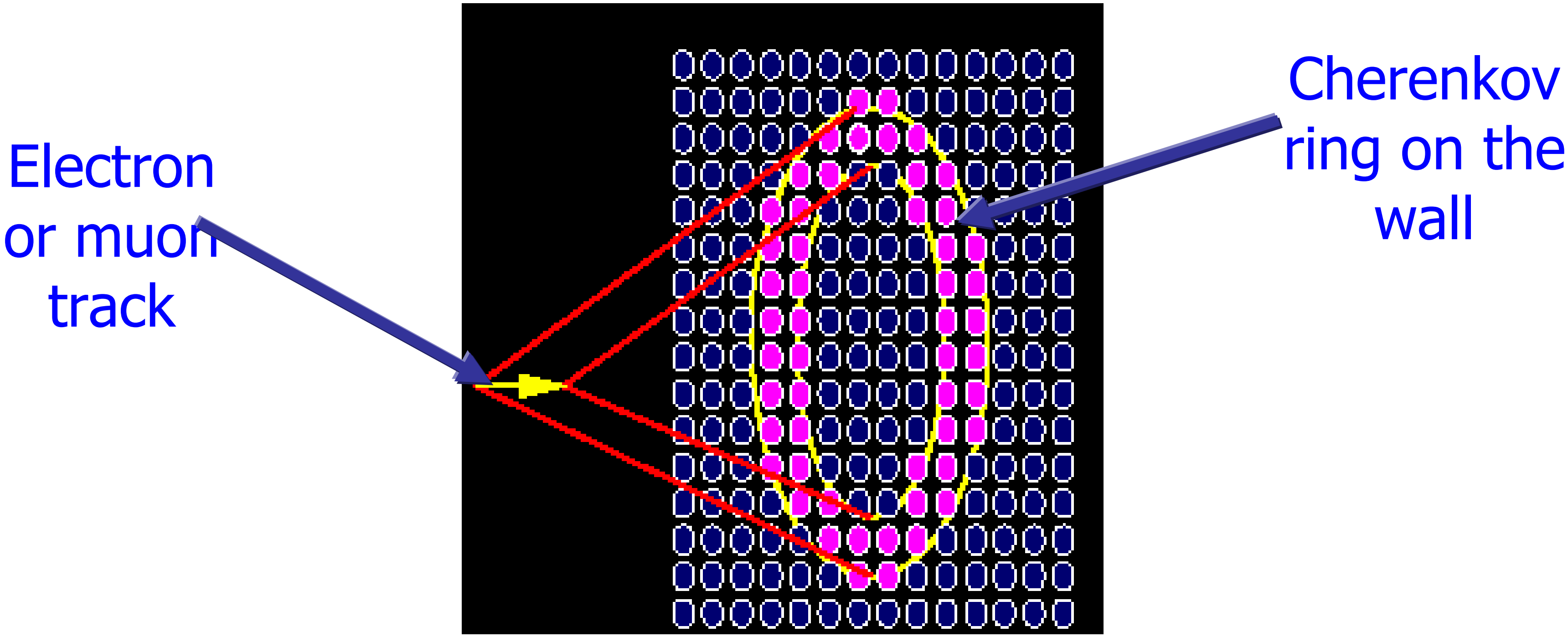


⇨ Cherenkov radiation

Cherenkov Radiation



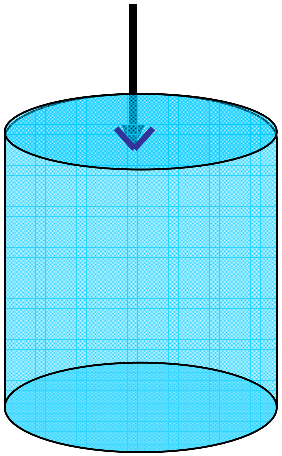
Detecting neutrinos

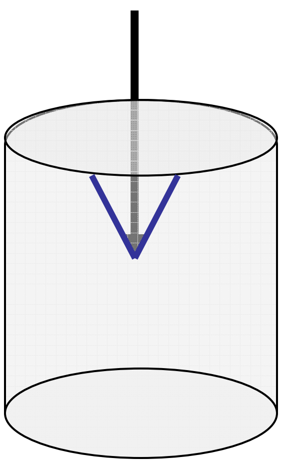


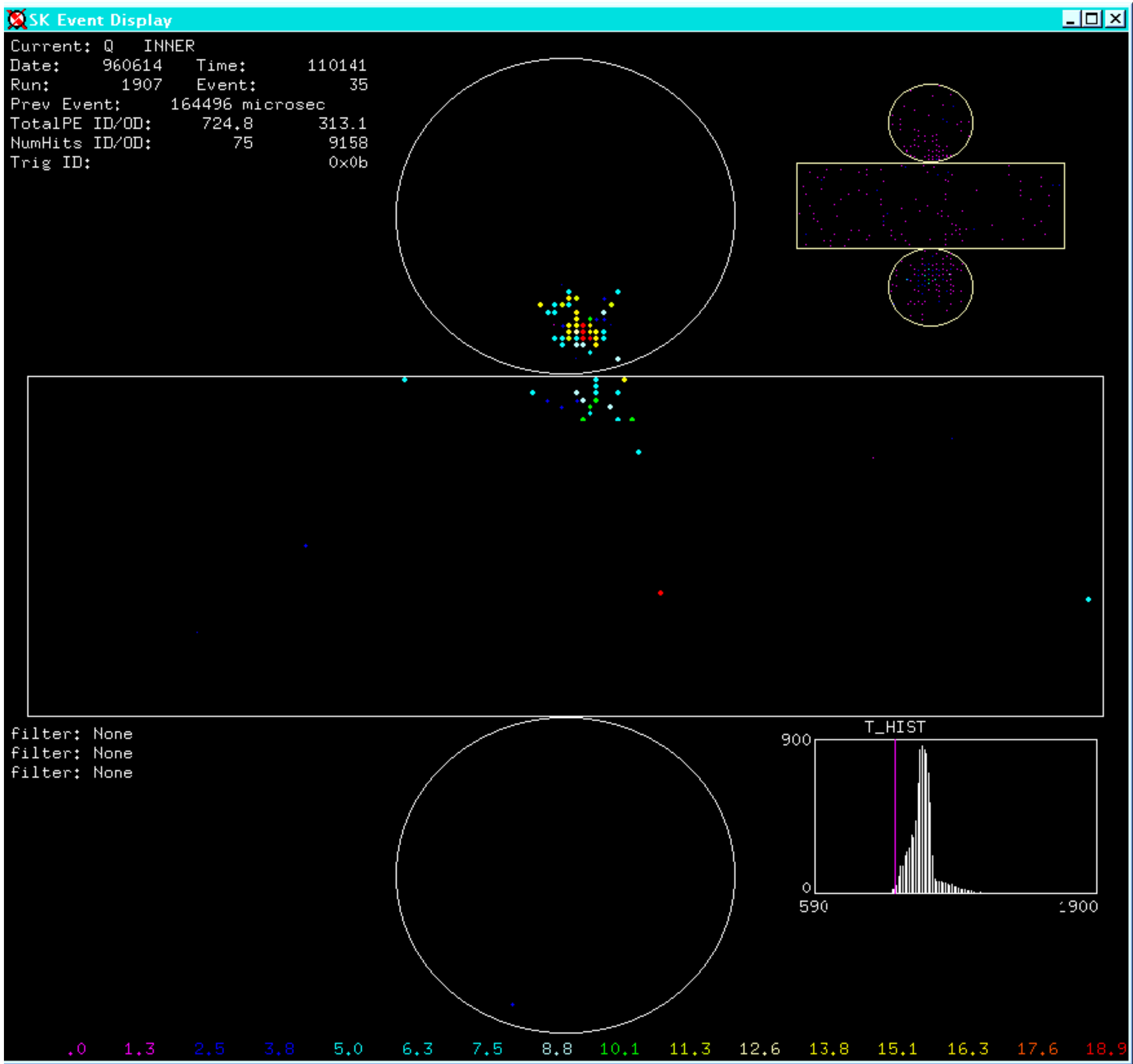
The pattern tells us the energy and type of particle

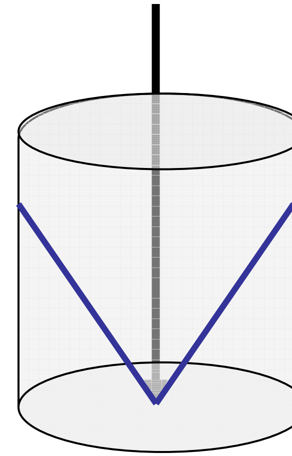
We can easily tell muons from electrons

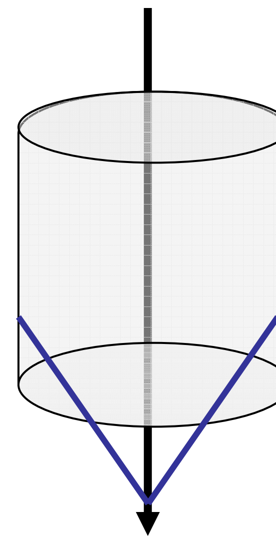
A muon going through the detector



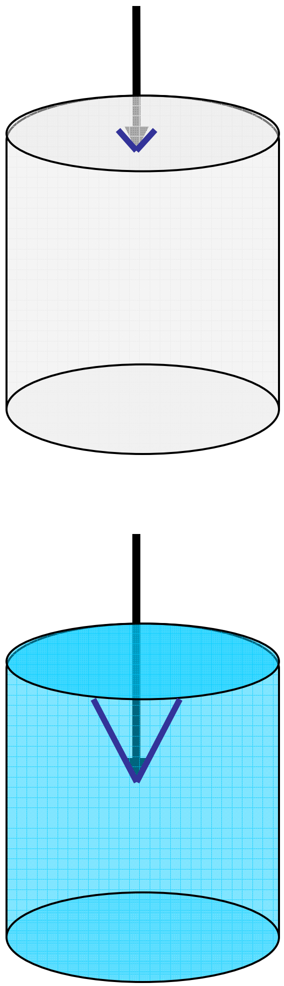


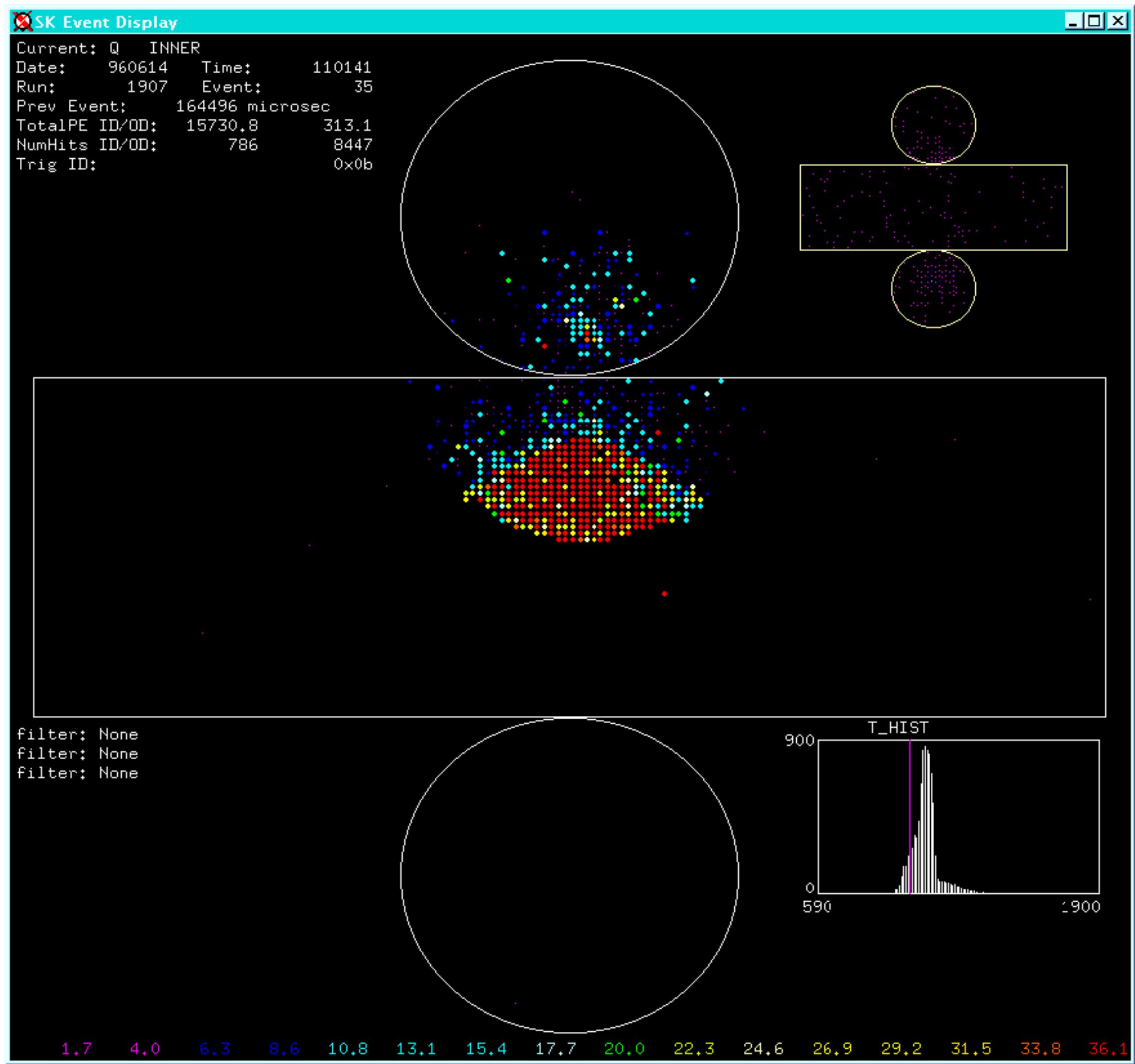


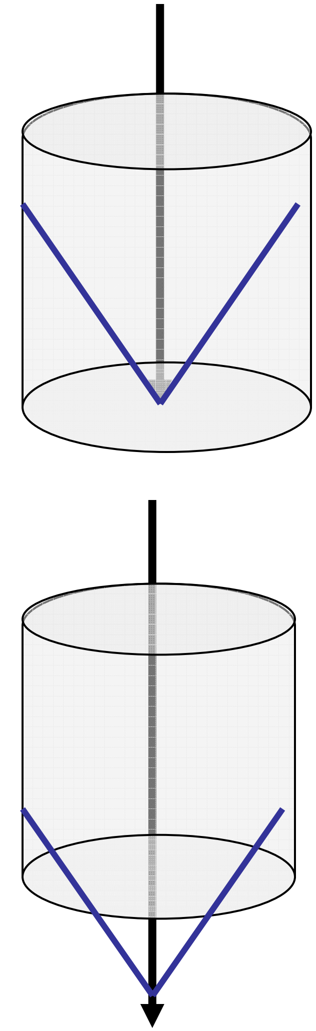




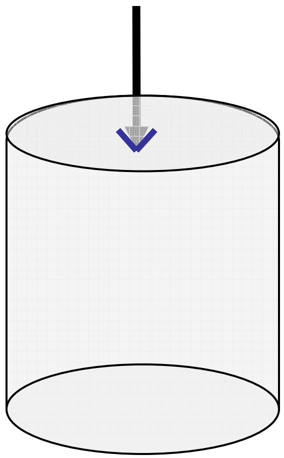
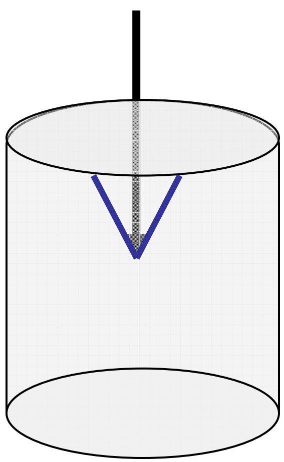
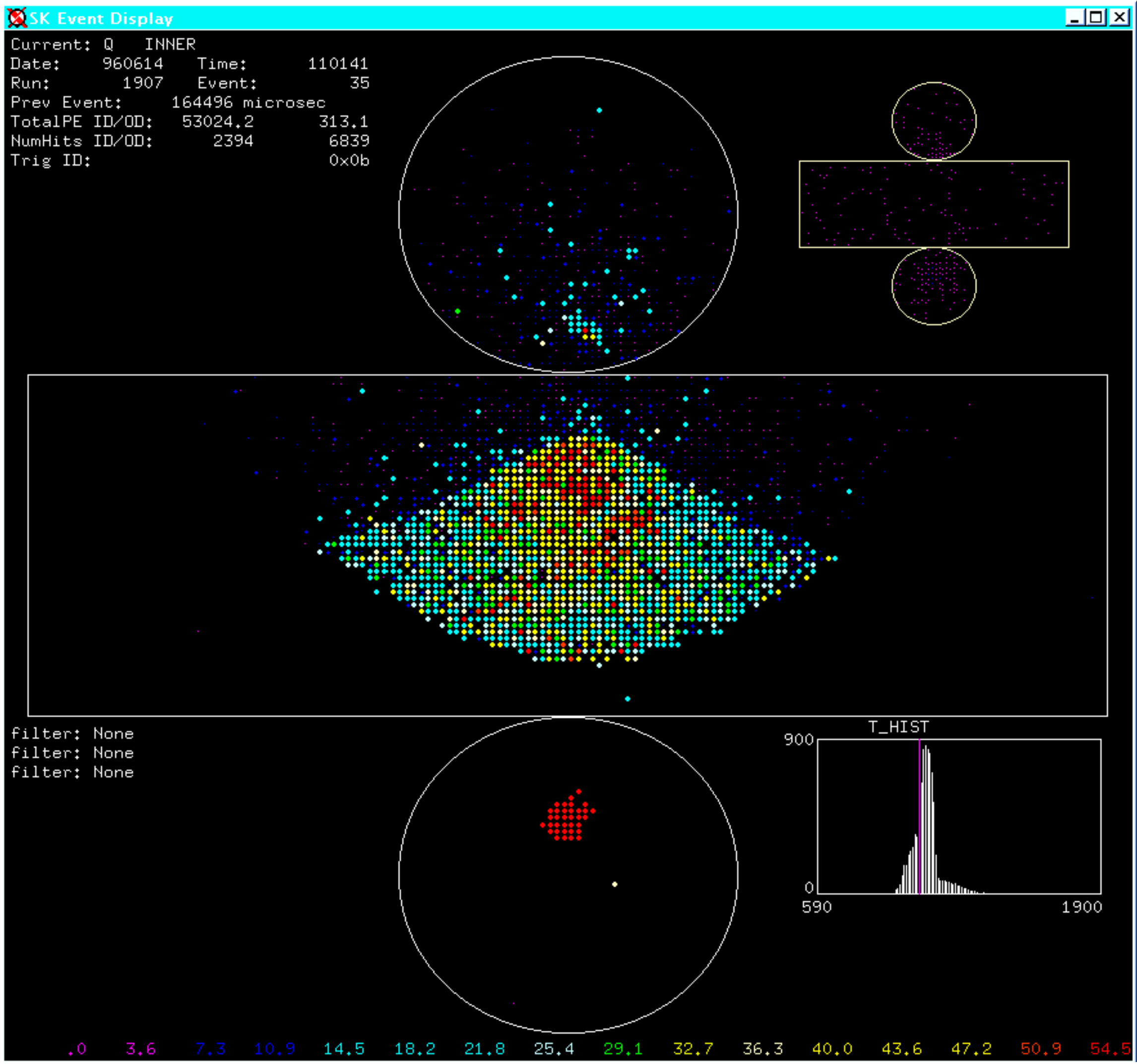
A muon going through the detector

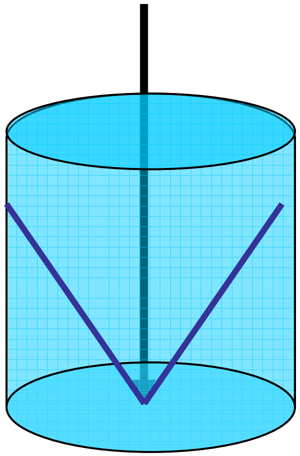
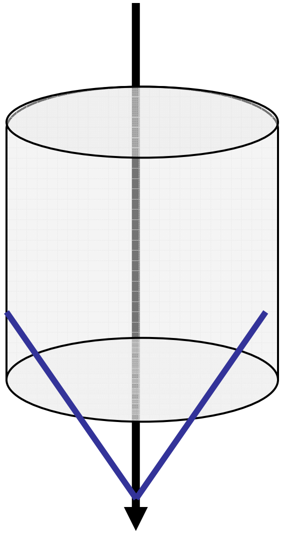




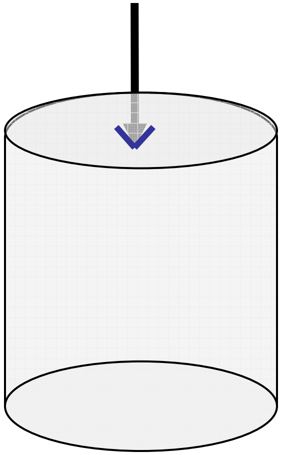


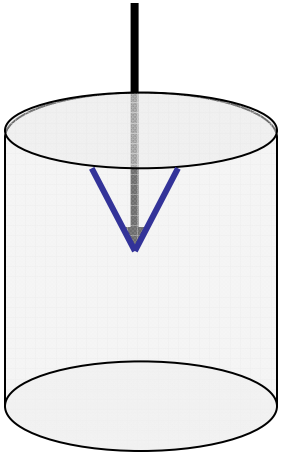
A muon going through the detector

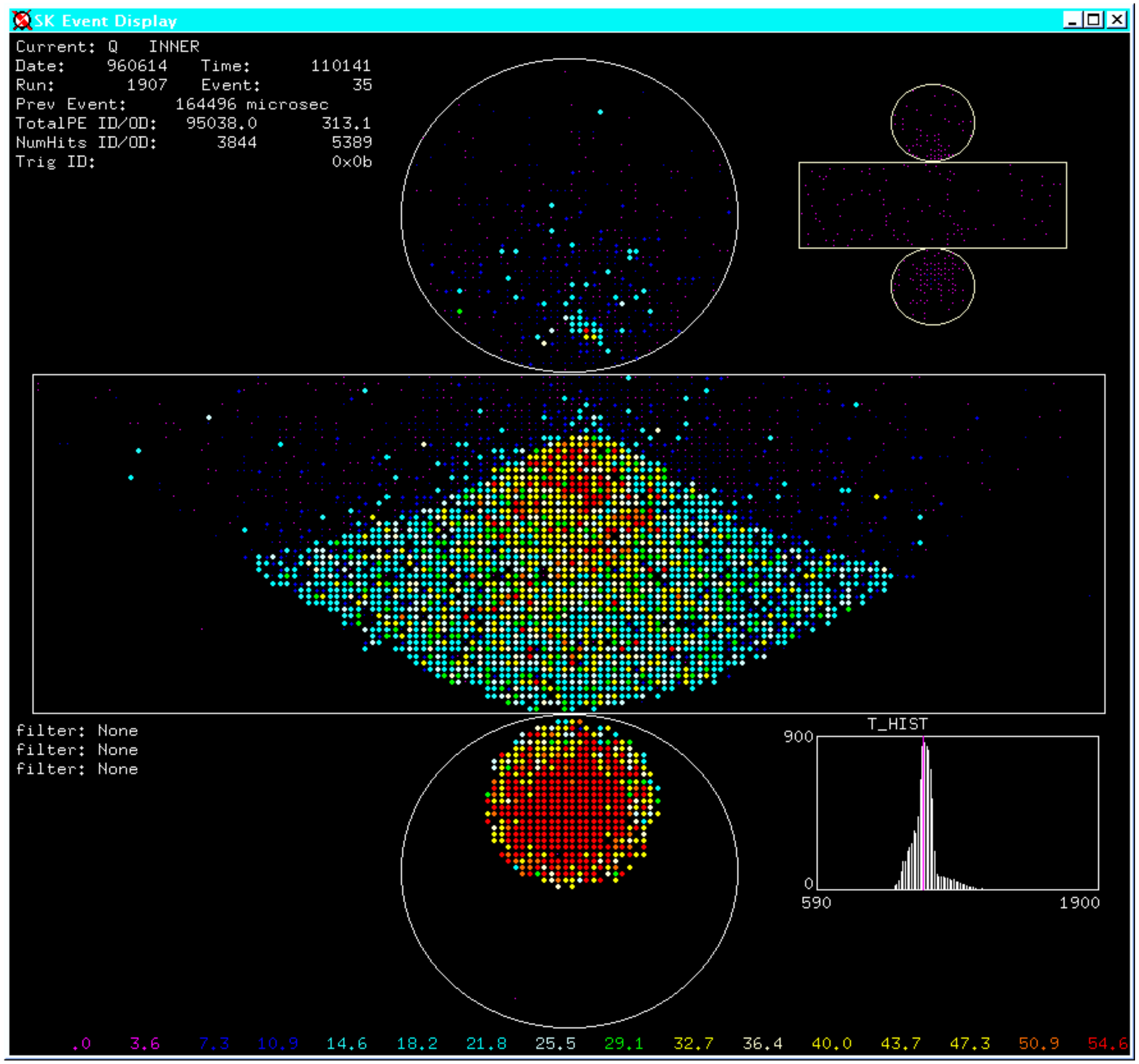




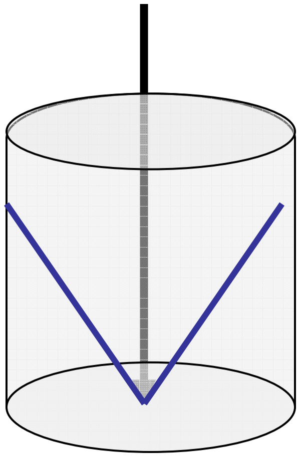



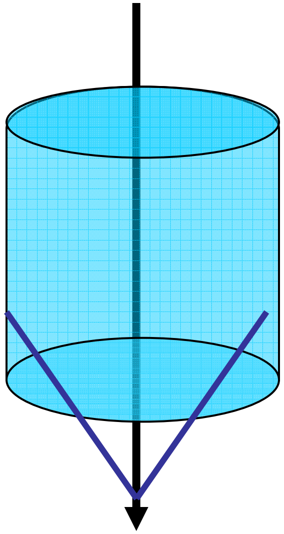
A muon going through the detector



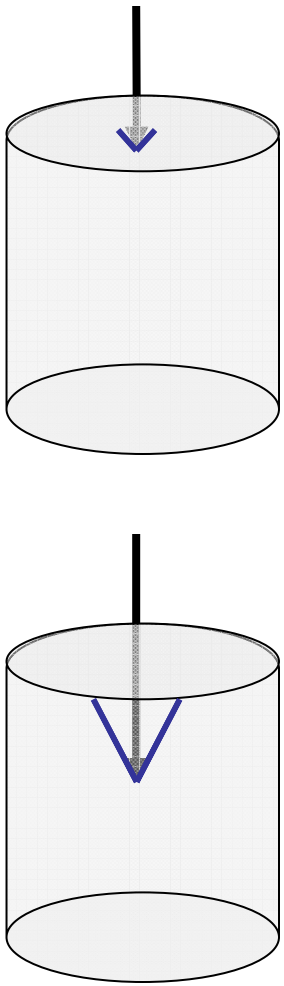


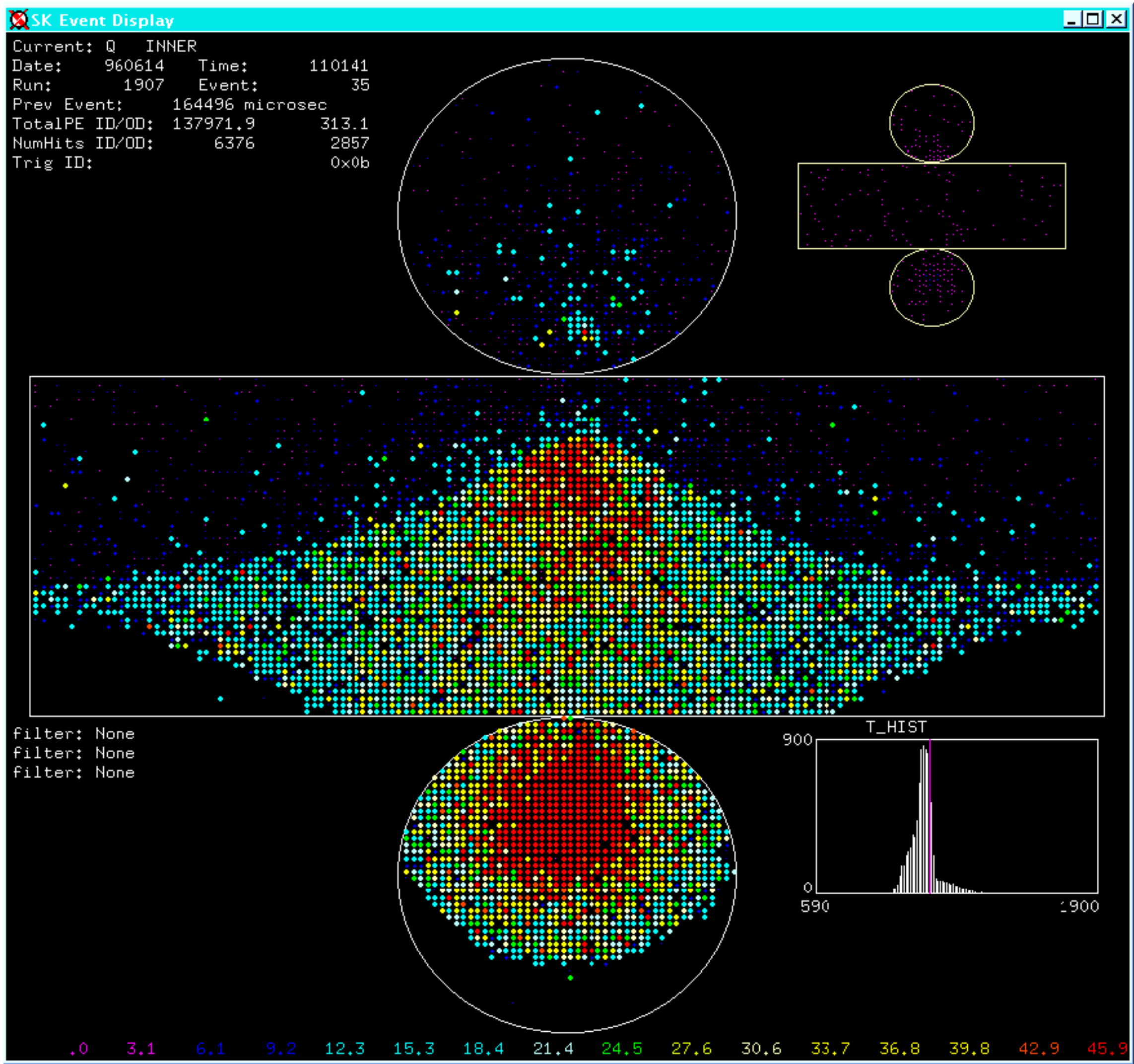


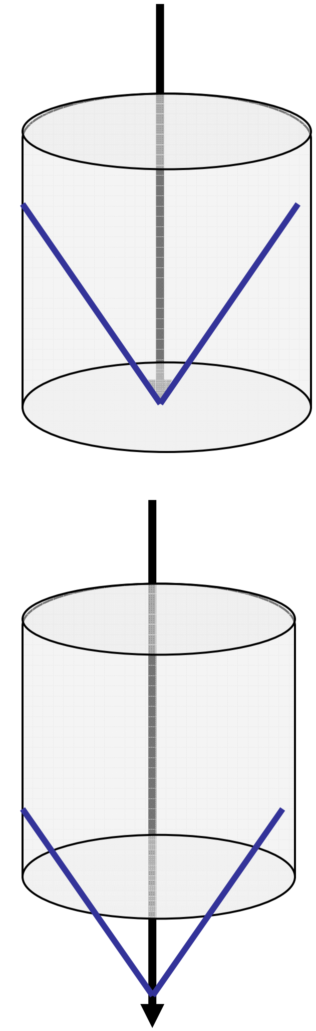




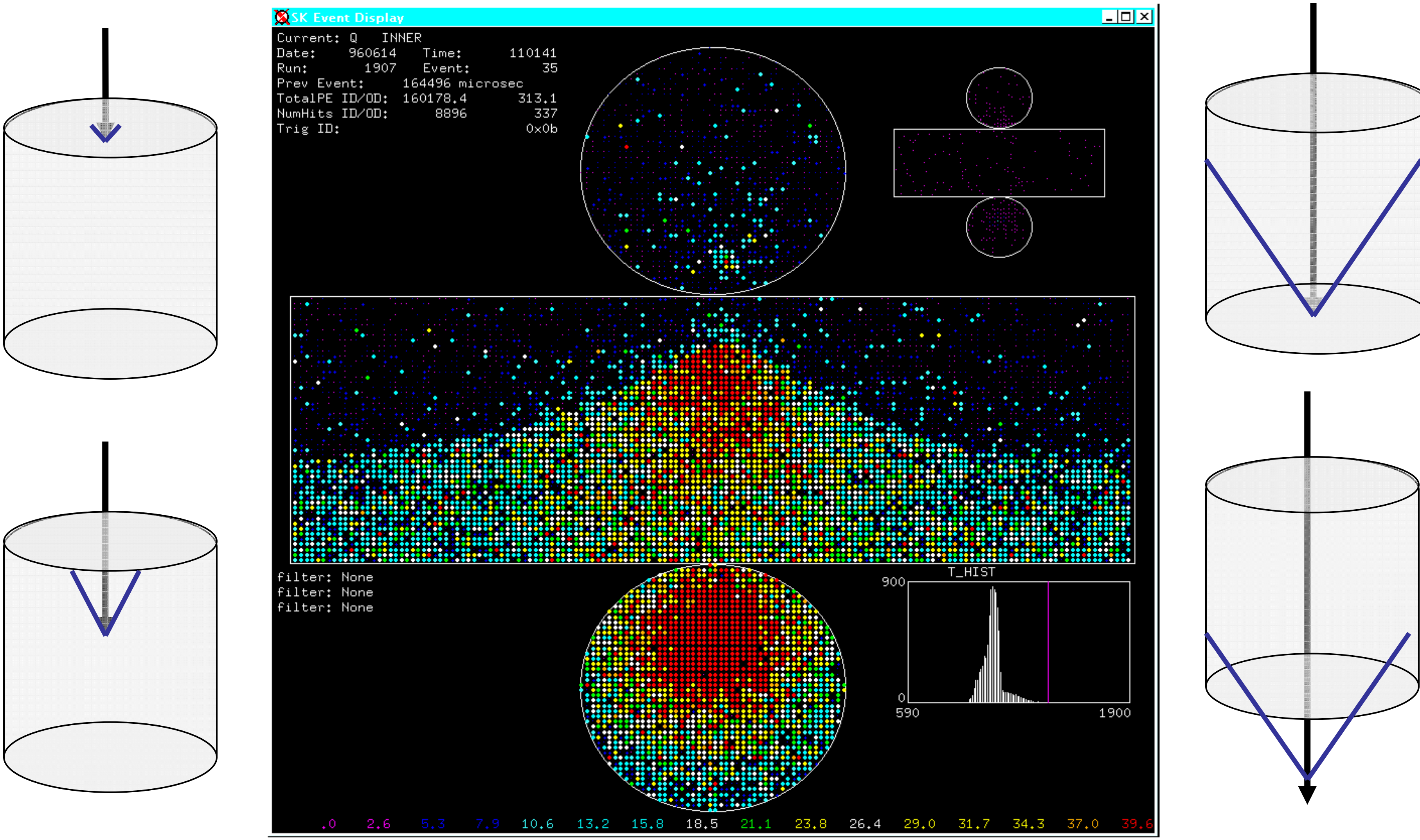
A muon going through the detector



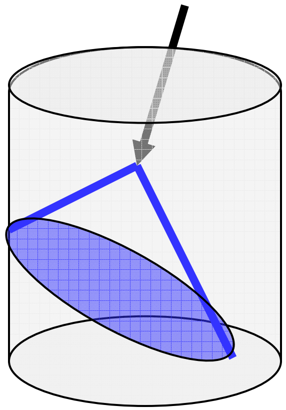


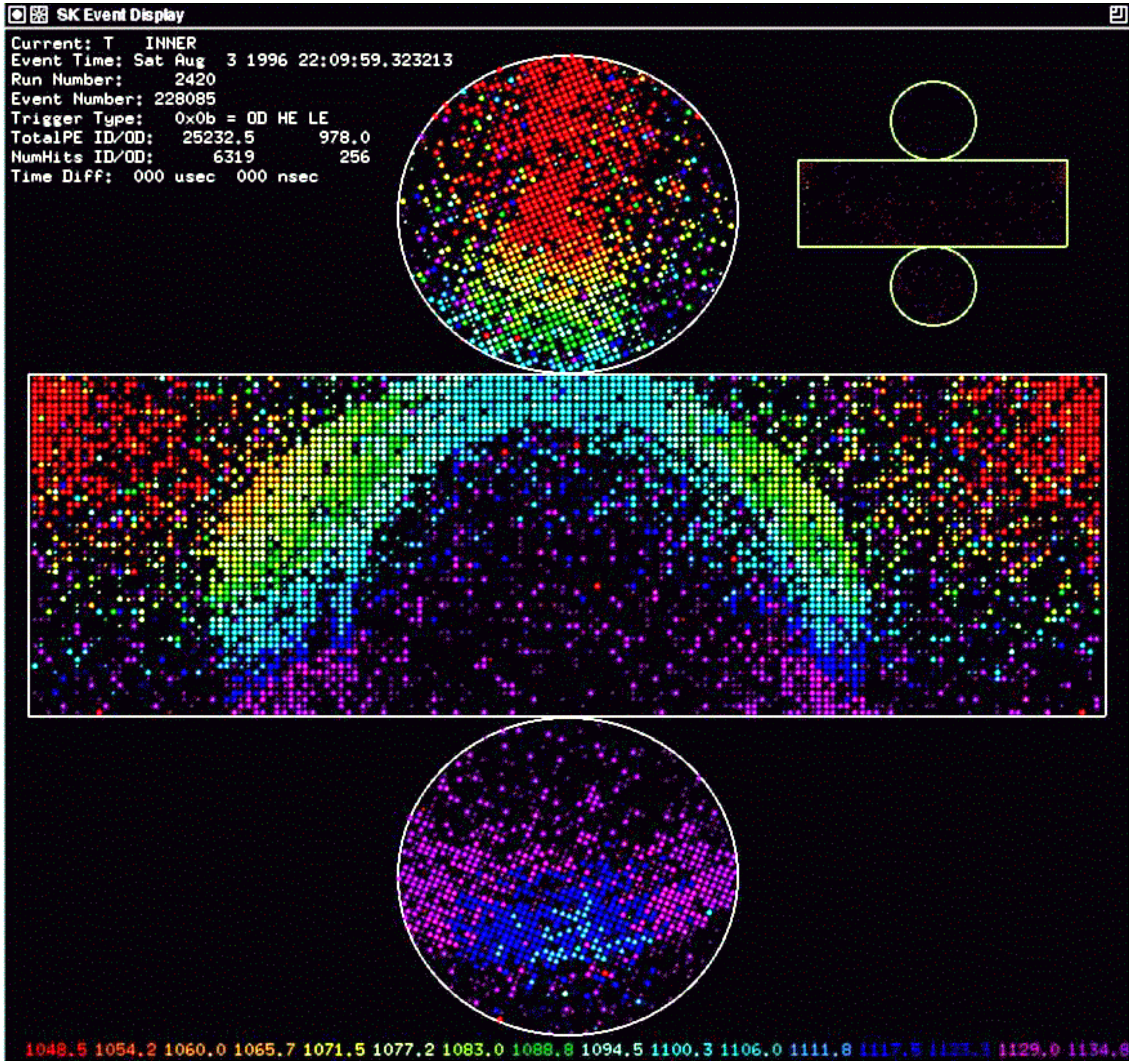


A muon going through the detector

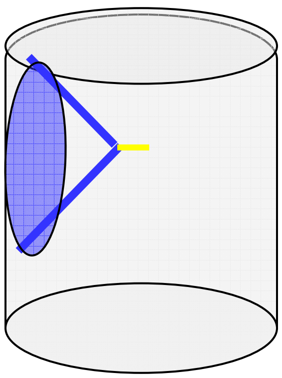


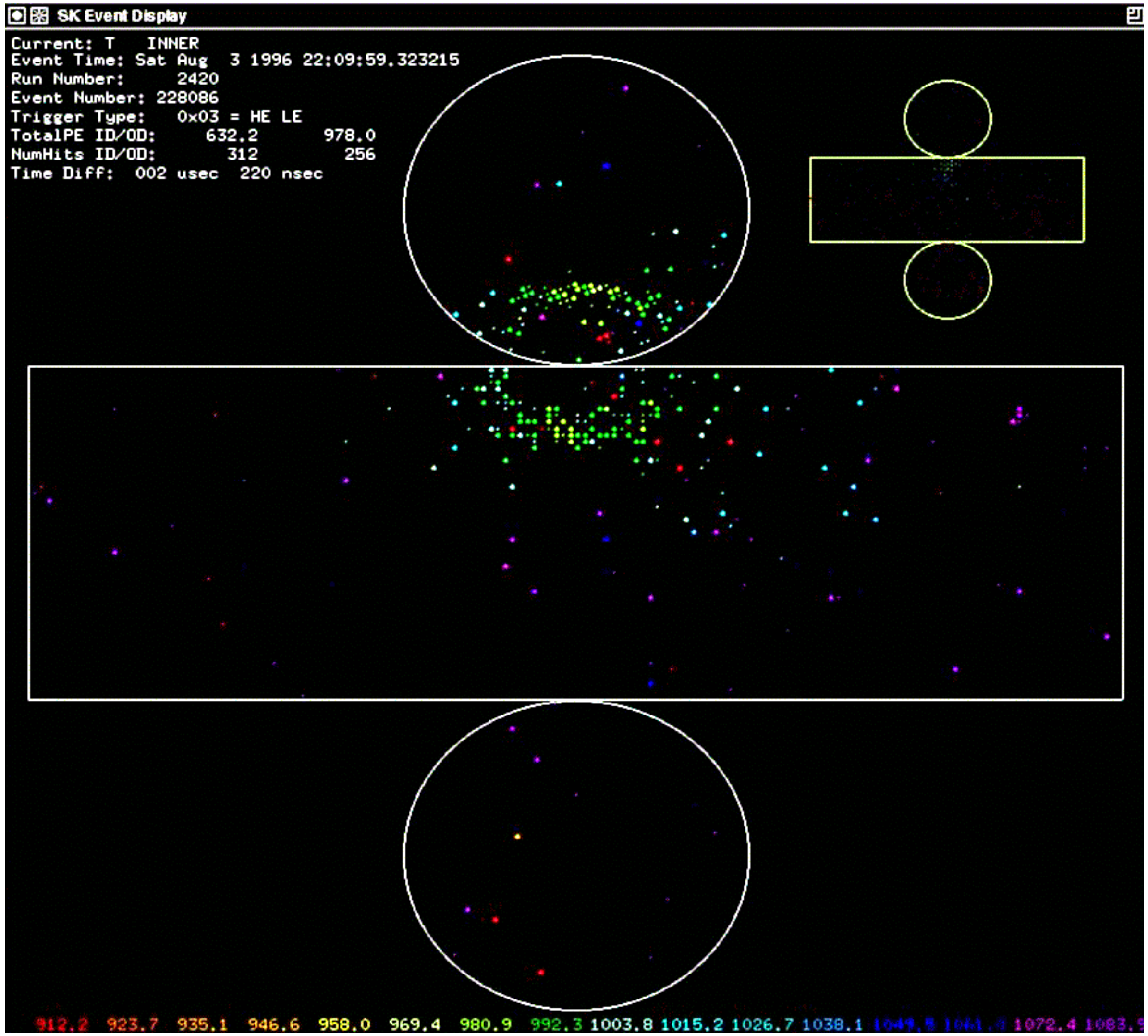
Stopping Muon



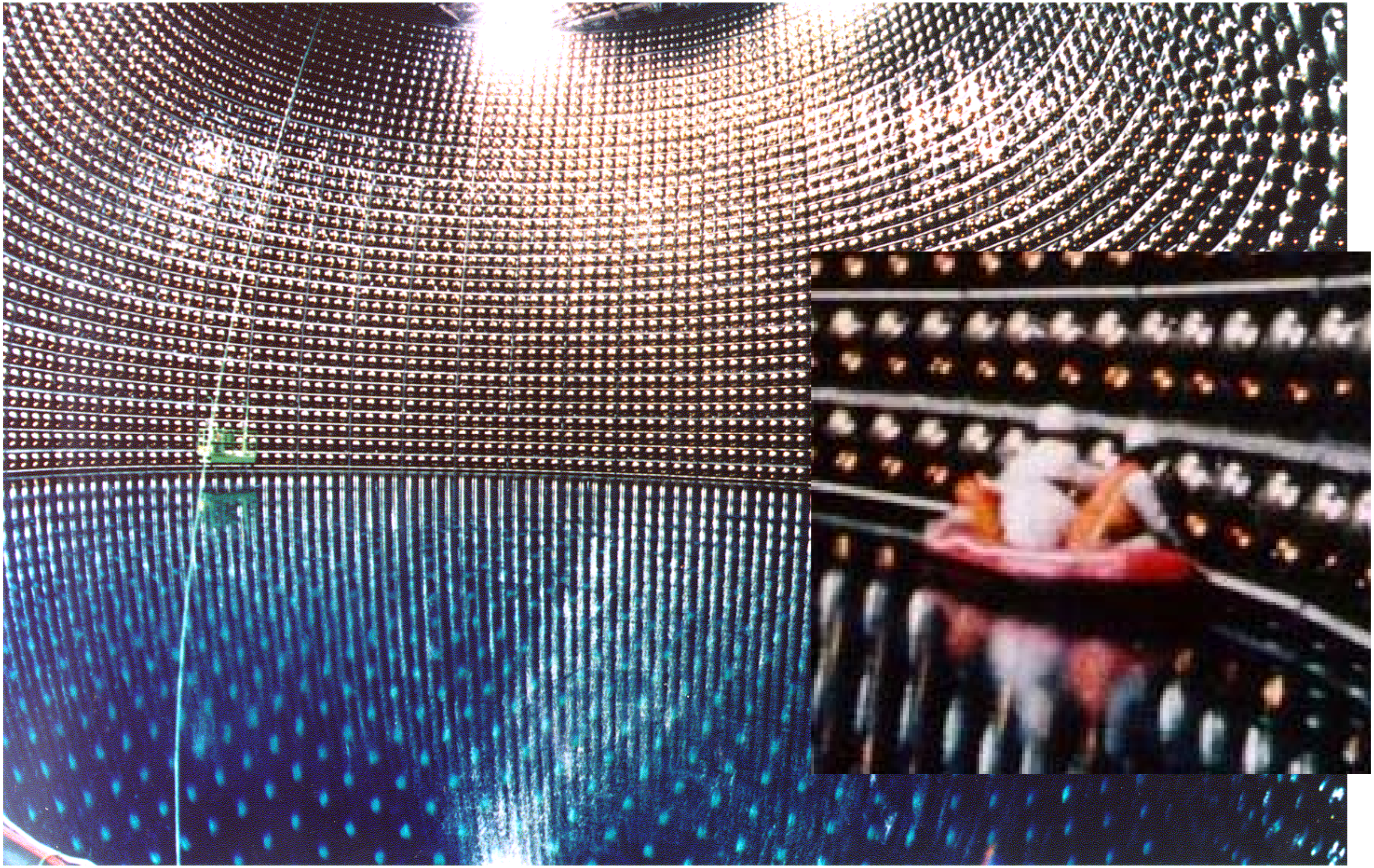


Stopping Muon – Decay Electron



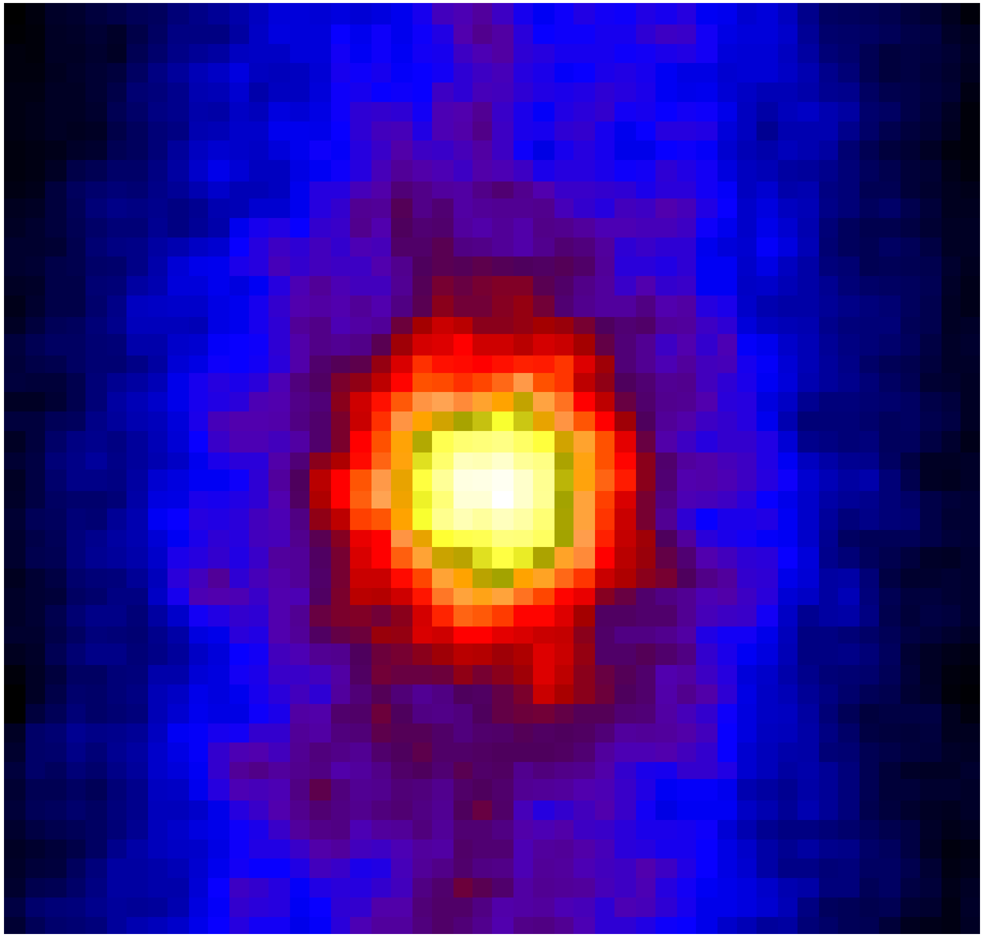


Super-Kamiokande

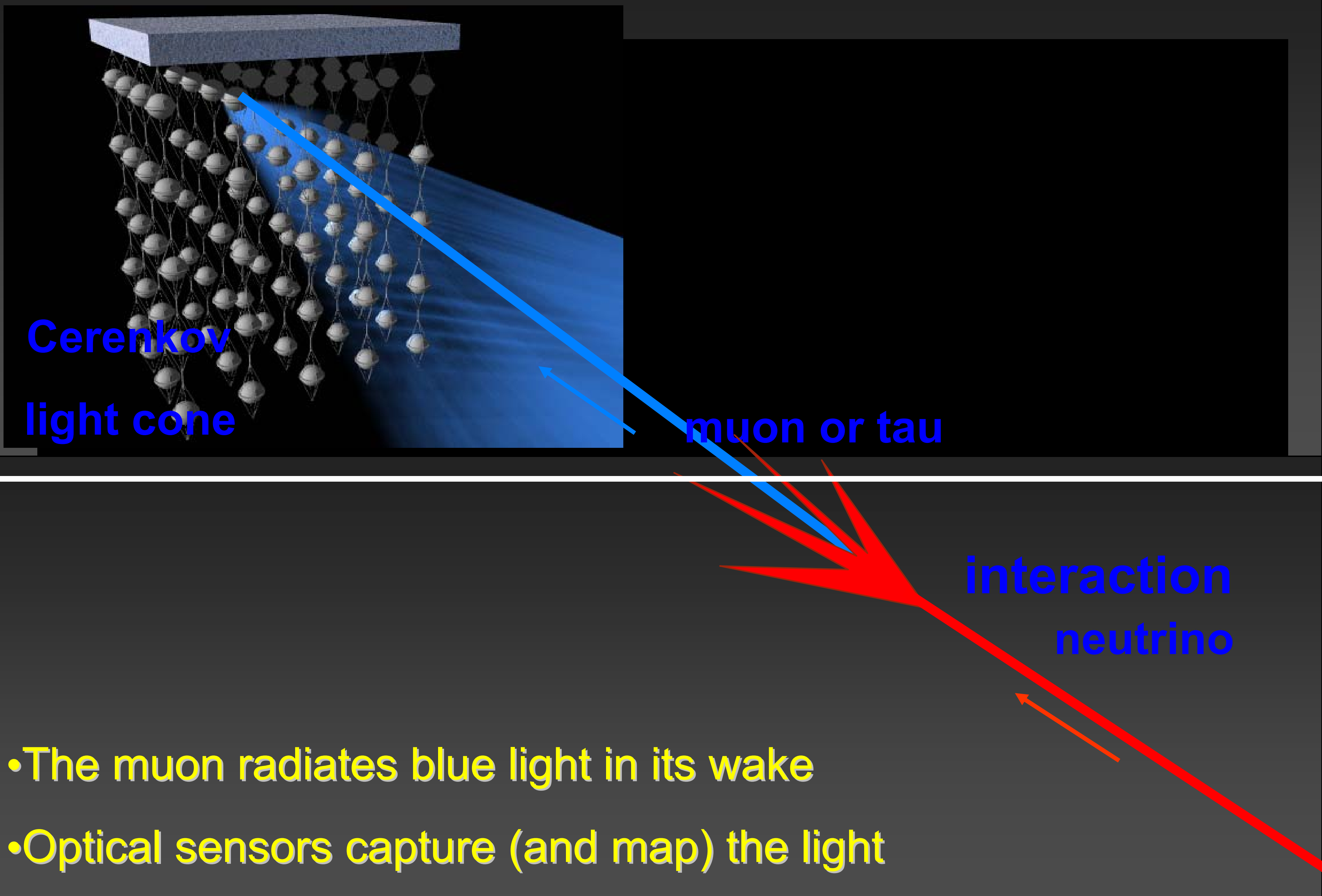


Neutrino Picture of the Sun

Image of the sun taken from 1km underground using solar neutrinos

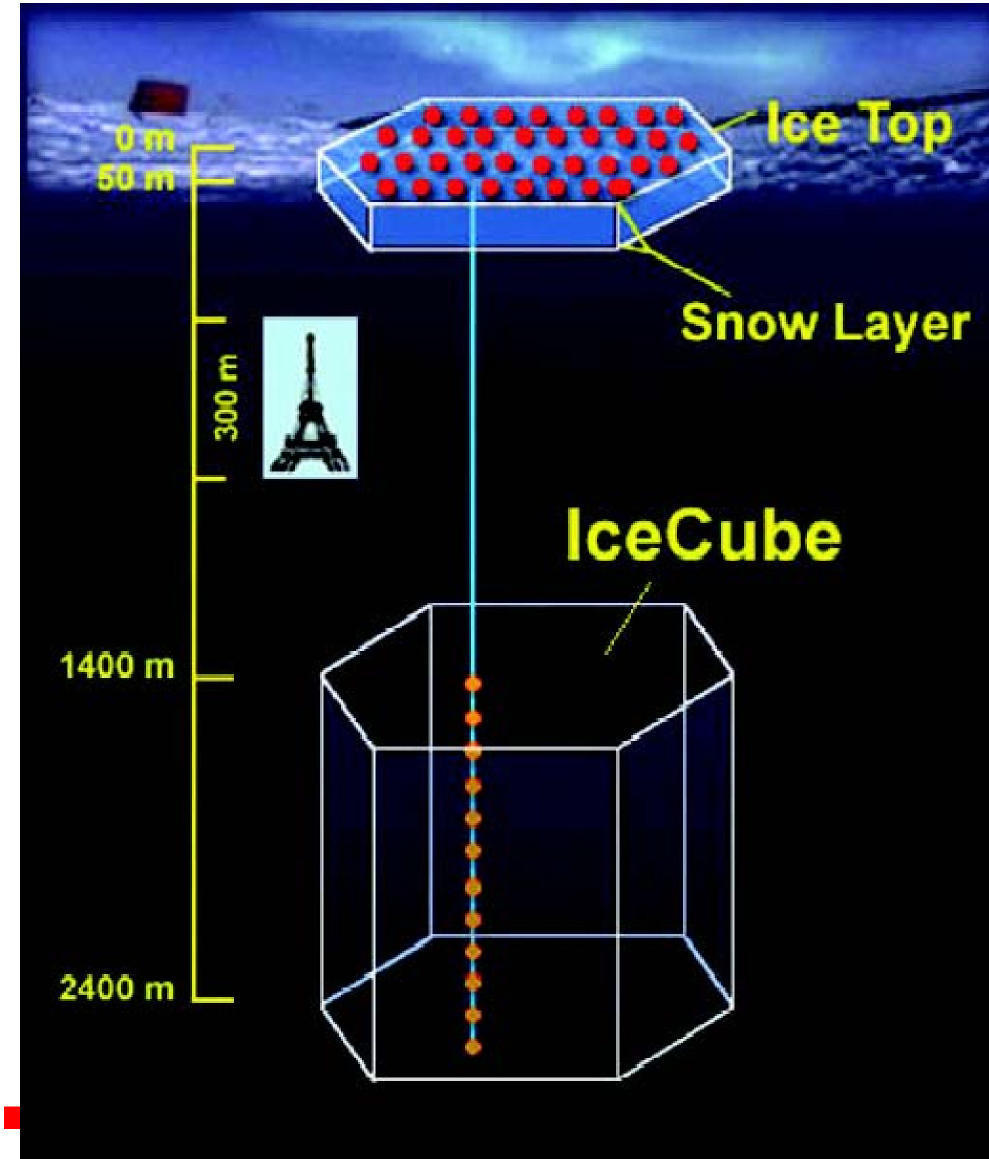


Detection Technique

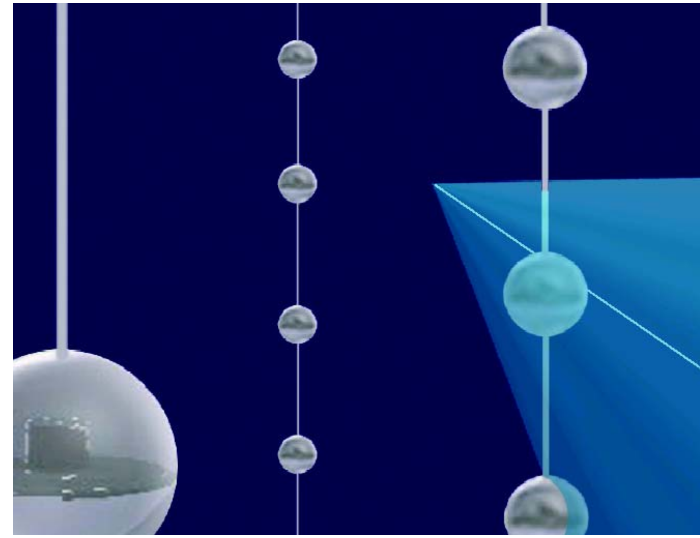


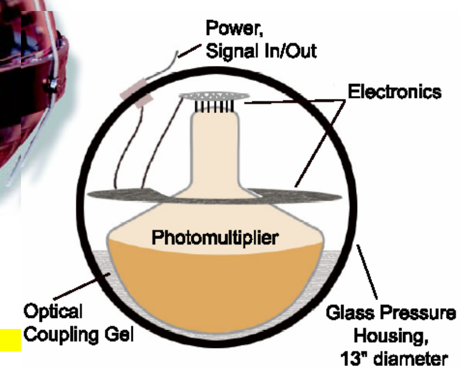
- The muon radiates blue light in its wake
- Optical sensors capture (and map) the light

Ice Cube



0 m
50 m
Ice Top
Snow Layer
300 m
IceCube
1400 m
2400 m





Power,
Signal In/Out
Electronics
Photomultiplier
Optical
Coupling Gel
Glass Pressure
Housing,
13" diameter

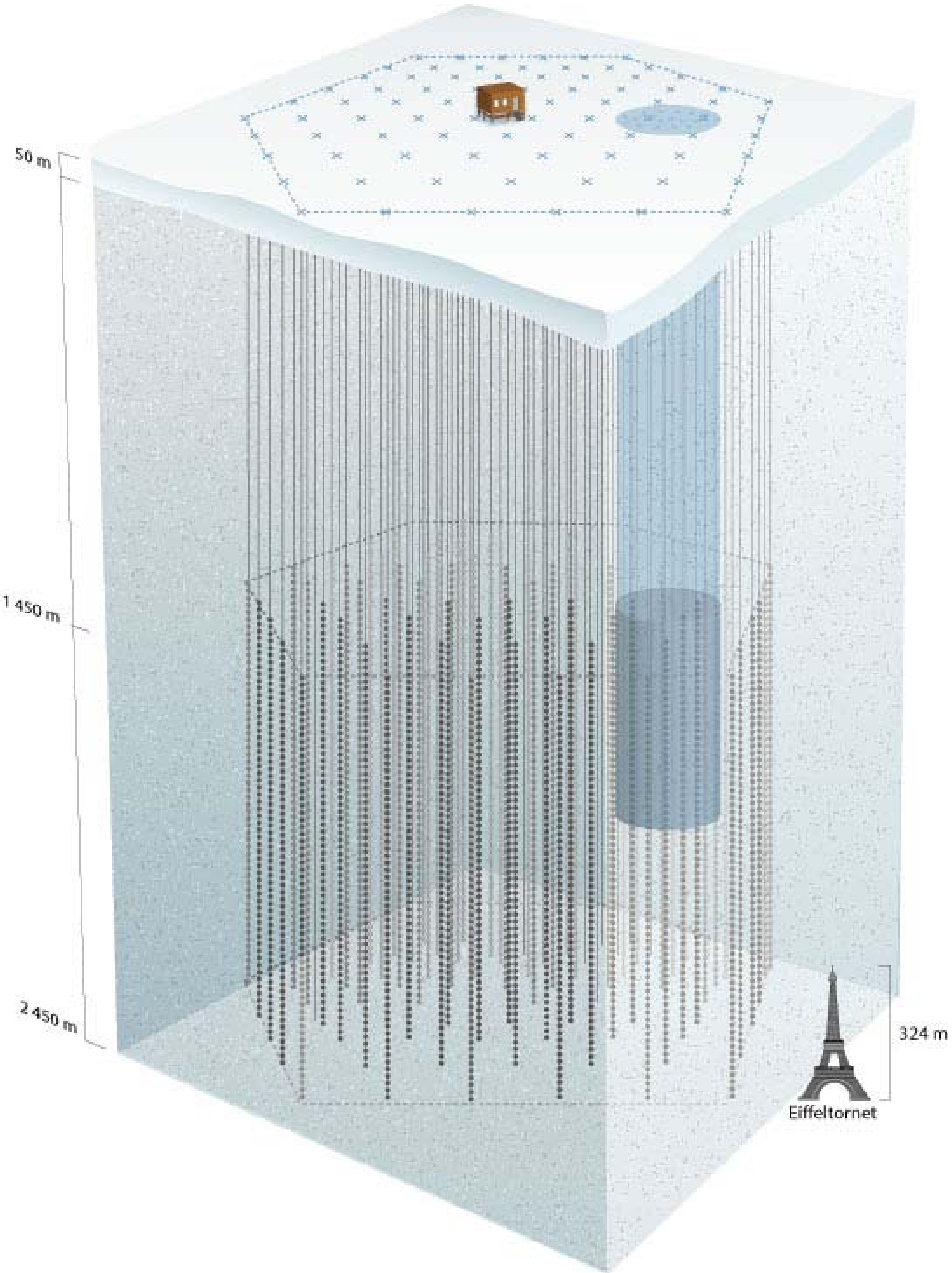
IceCube Neutrino Observatory

IceTop shower array

80 pairs of Cherenkov tanks

IceCube

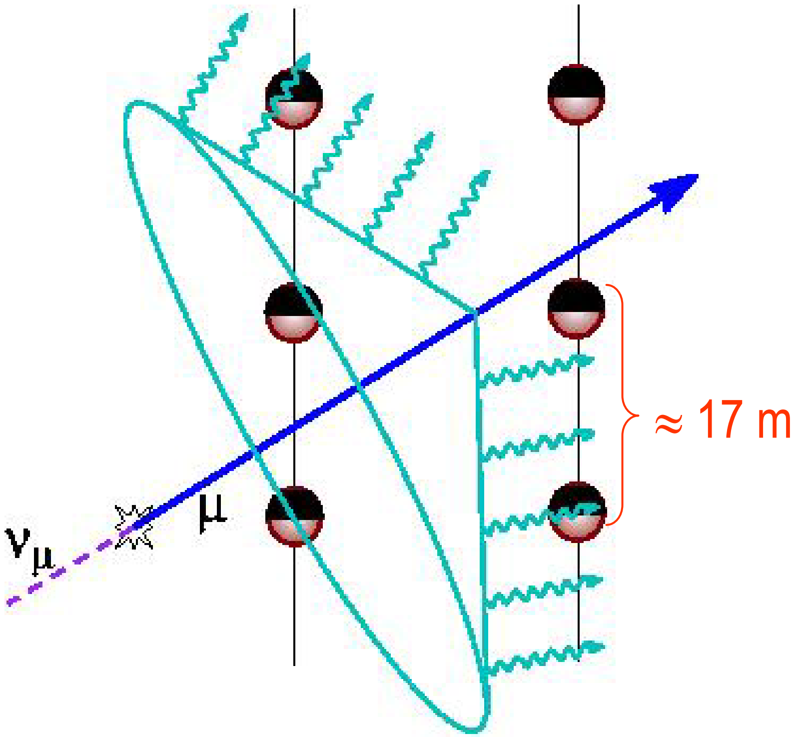
4800 optical modules on 80 strings

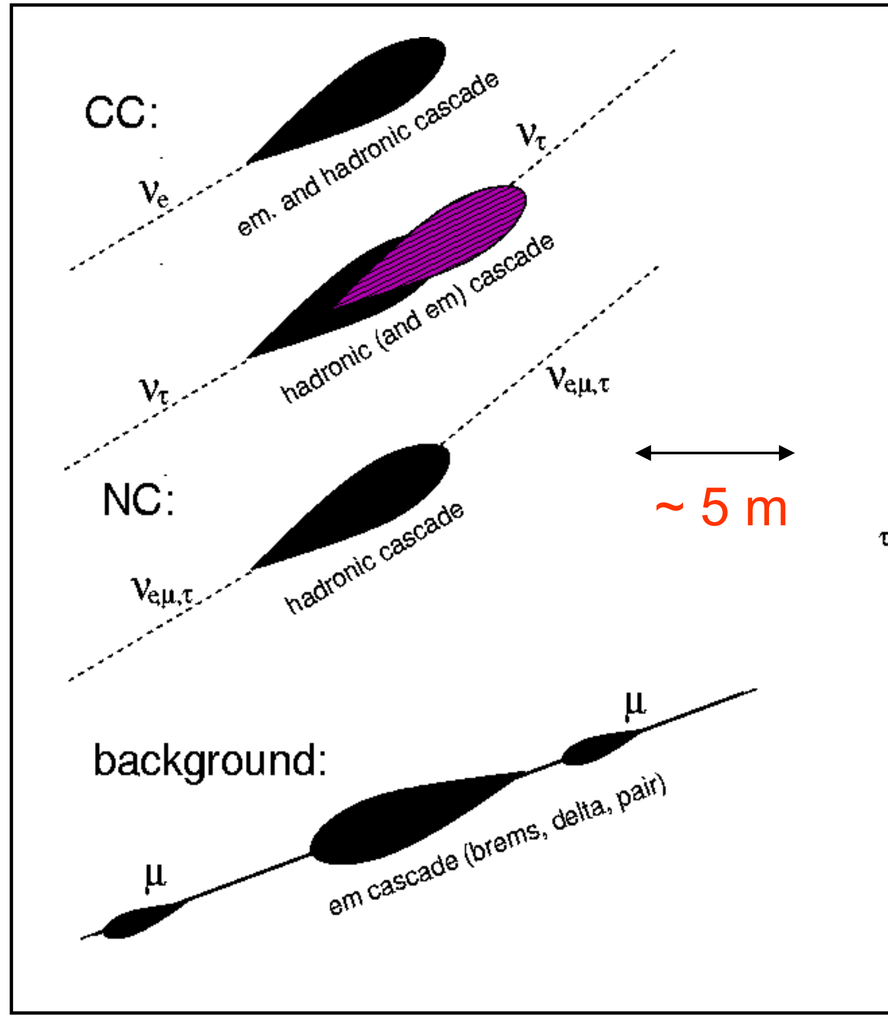


Detection of ν_e, ν_μ, ν_τ

O(km) long muon tracks

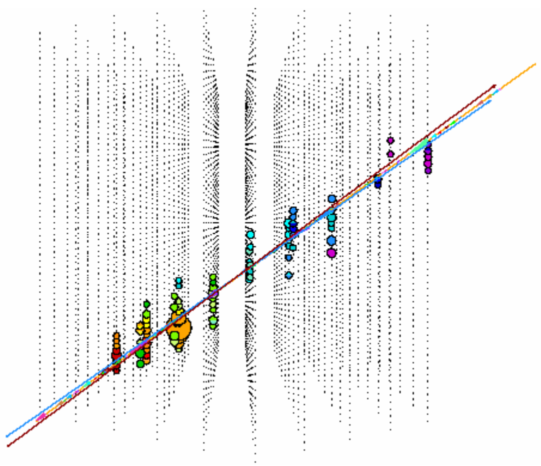
Electromagnetic and hadronic cascades



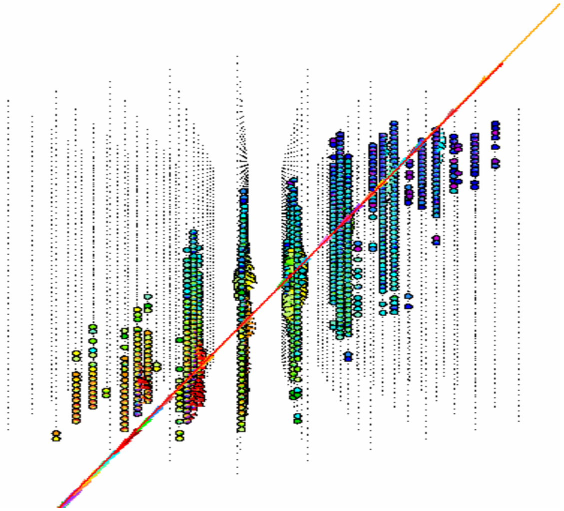


direction determination
by cherenkov light timing

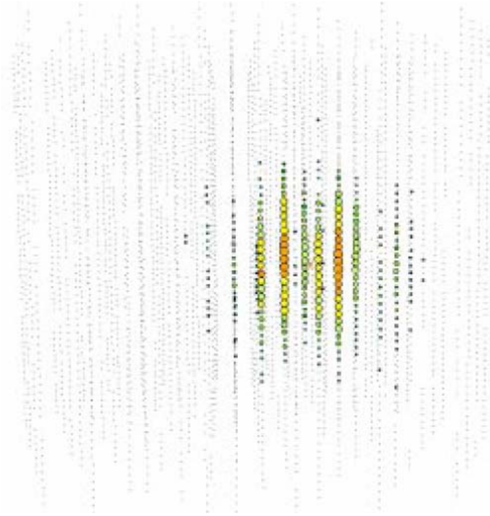
Determining Energy



10 TeV μ



6 PeV μ



375 TeV
Cascade

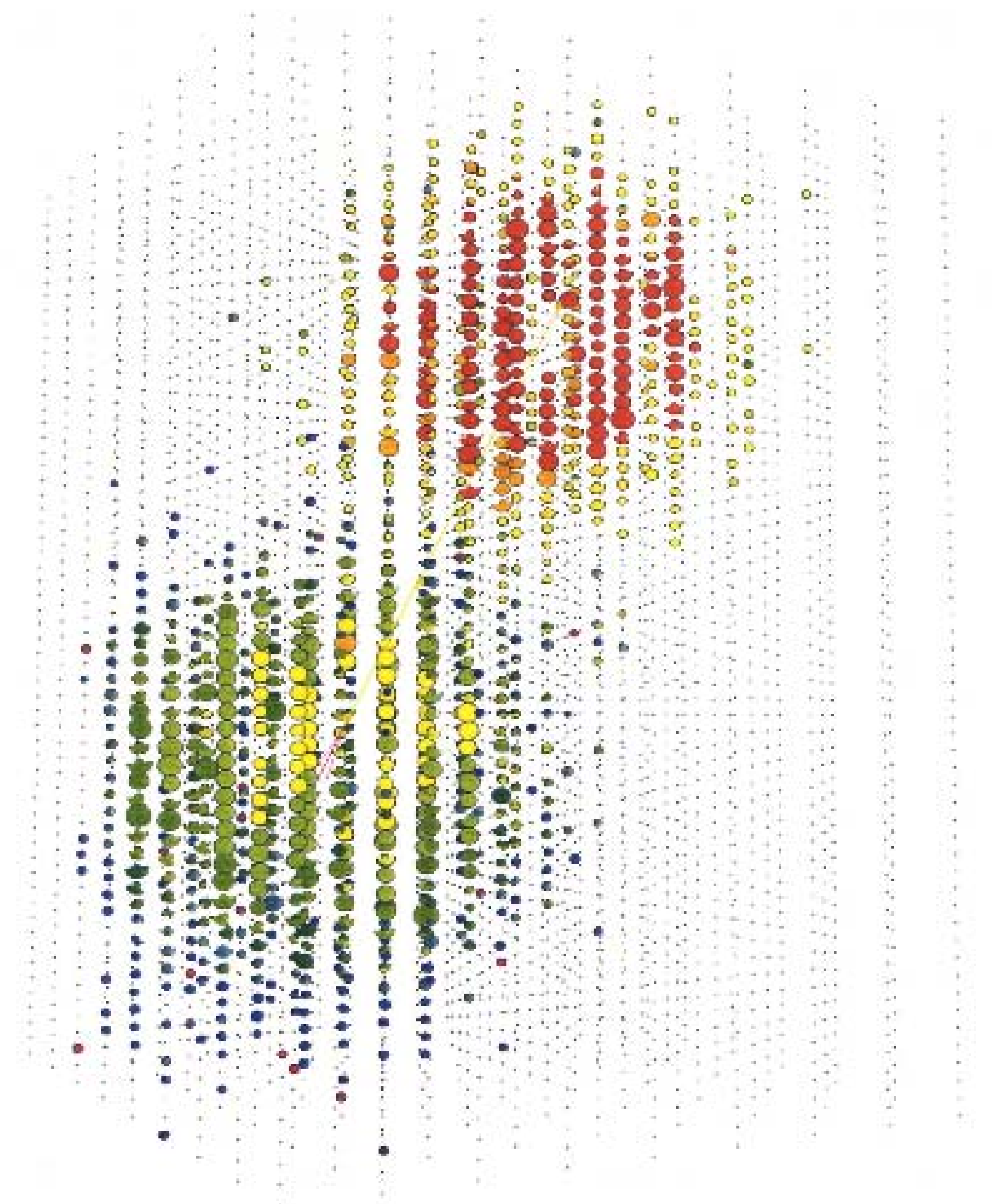
Measure energy by counting the number of fired PMT.
(This is a very simple but robust method)

ν_τ Double Bang

Learned, Pakvasa, 1995

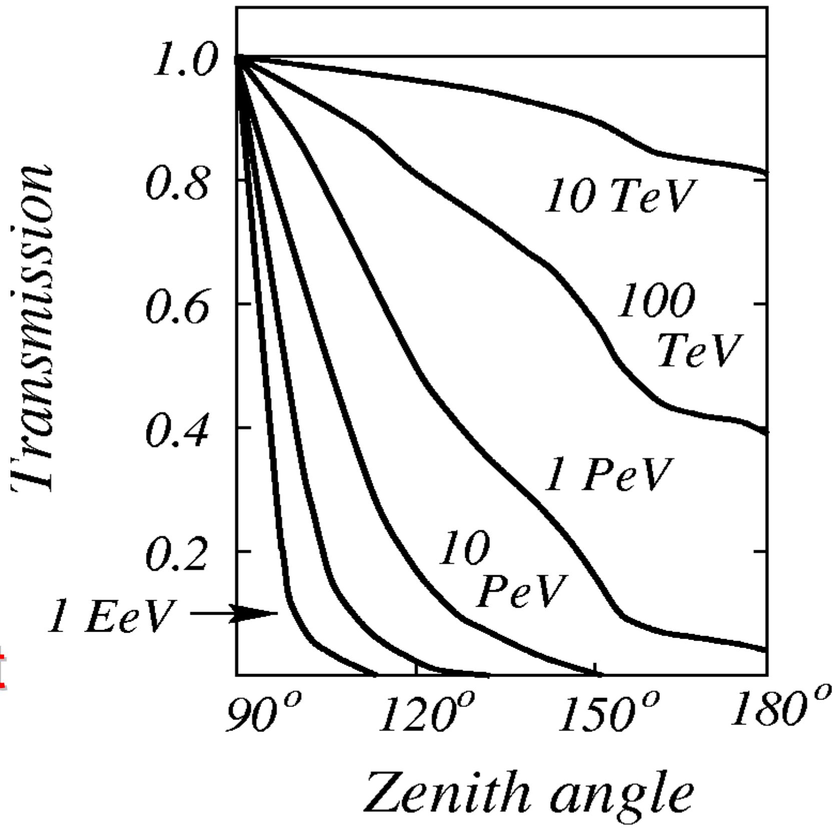
$$\nu_\tau + \mathbf{N} \dashrightarrow \tau\text{-} + \mathbf{X}$$
$$\downarrow$$
$$\nu_\tau + \mathbf{X} \quad \mathbf{(82\%)}$$

E << 1PeV: Single cascade
(2 cascades coincide)
E ≈ 1PeV: Double bang
E >> 1 PeV: partially contained
(reconstruct incoming tau track and cascade from decay)



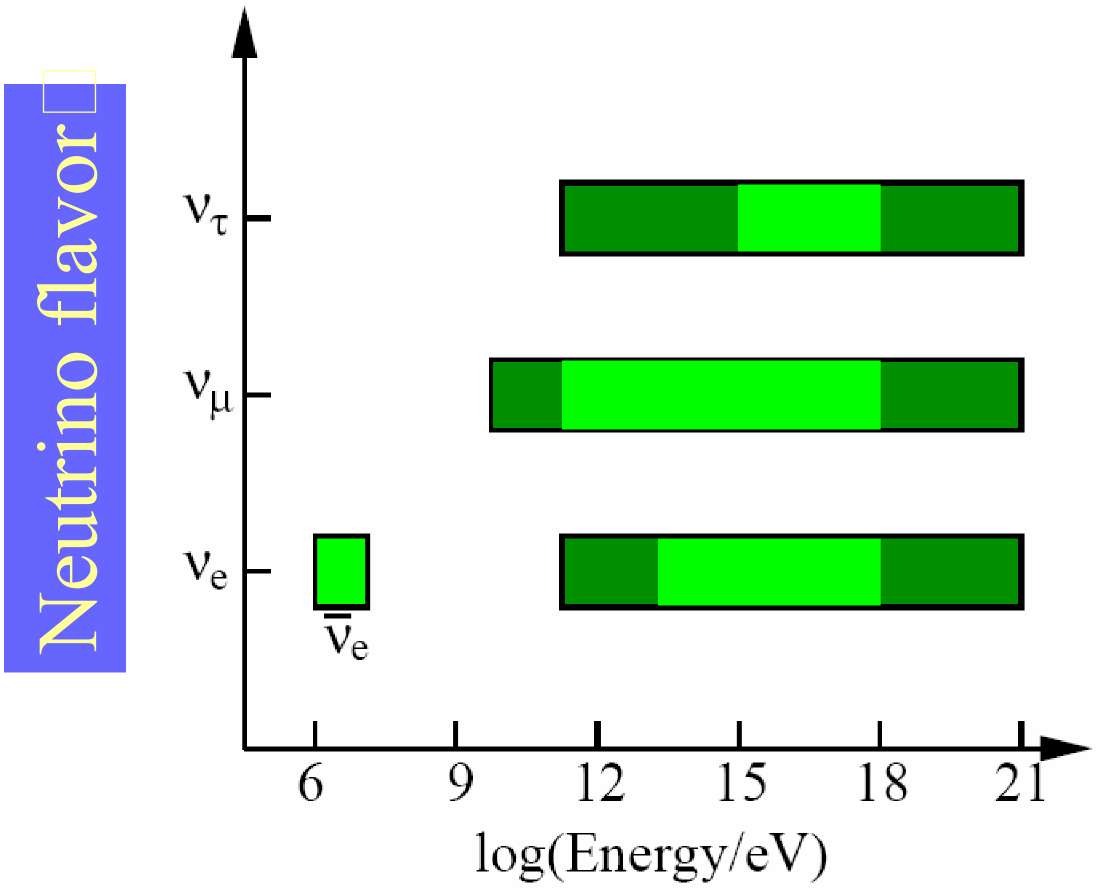
Tau Transparency/Regeneration

- ν_e and ν_μ are absorbed in the Earth via charged current interactions (muons range out)
- Above ~500 TeV the Earth is opaque to ν_e & ν_μ.
  - *70 TeV: interaction length = earth diameter*
- But, the Earth never becomes completely opaque to ν_τ
- Due to the short τ lifetime, τ's produced in ν_τ charged-current interactions decay back into ν_τ
- Also, secondary ν_e & ν_μ. fluxes are produced in the tau decays.



IceCube Sensitivity

Neutrino ID (solid)
Energy and angle (shaded)

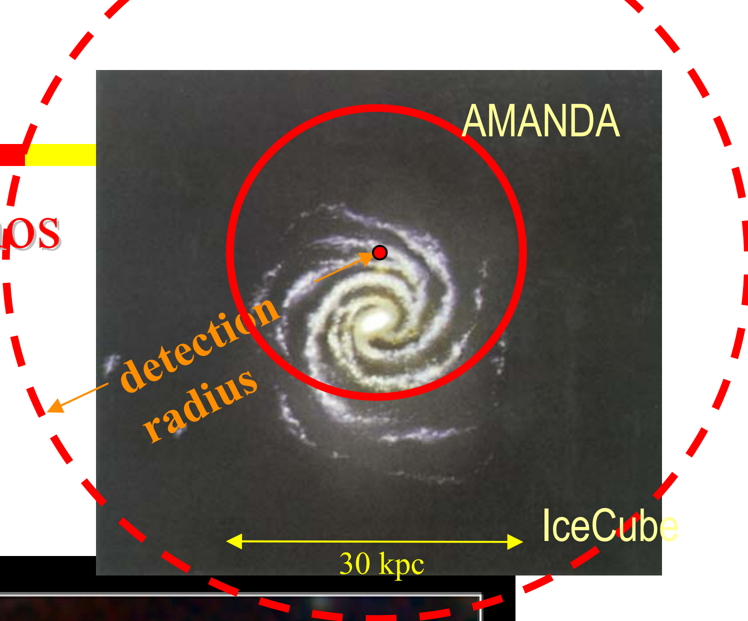


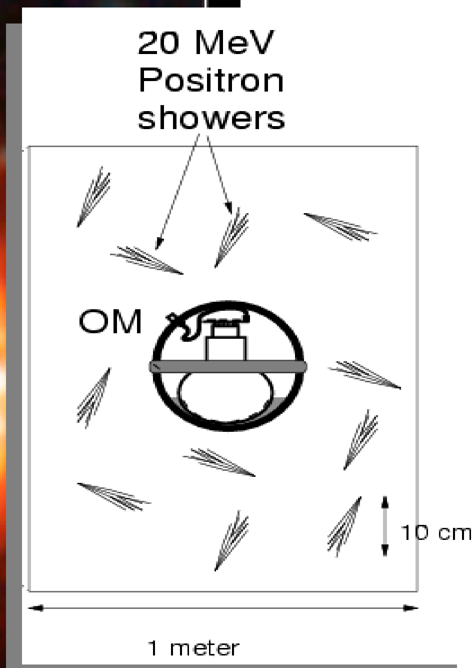
Supernova Detection

Expect a burst of low energy (MeV) neutrinos from core collapse of supernovae.

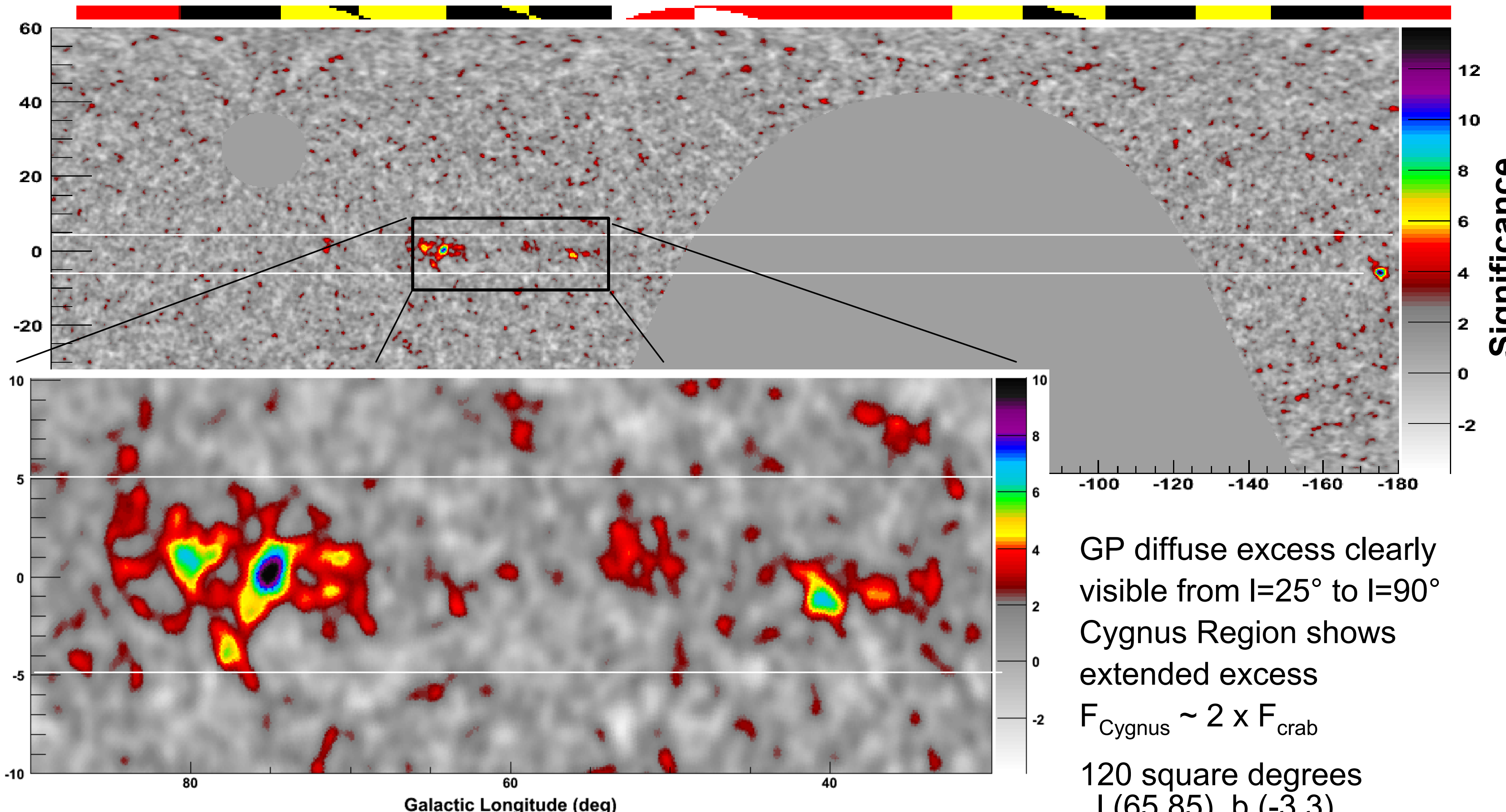
$$\bar{\nu}_e + p \rightarrow n + e^+$$

Detection via increase in dark noise rate.





A Look at the Galactic Plane at 10 TeV



GP diffuse excess clearly visible from l=25° to l=90°

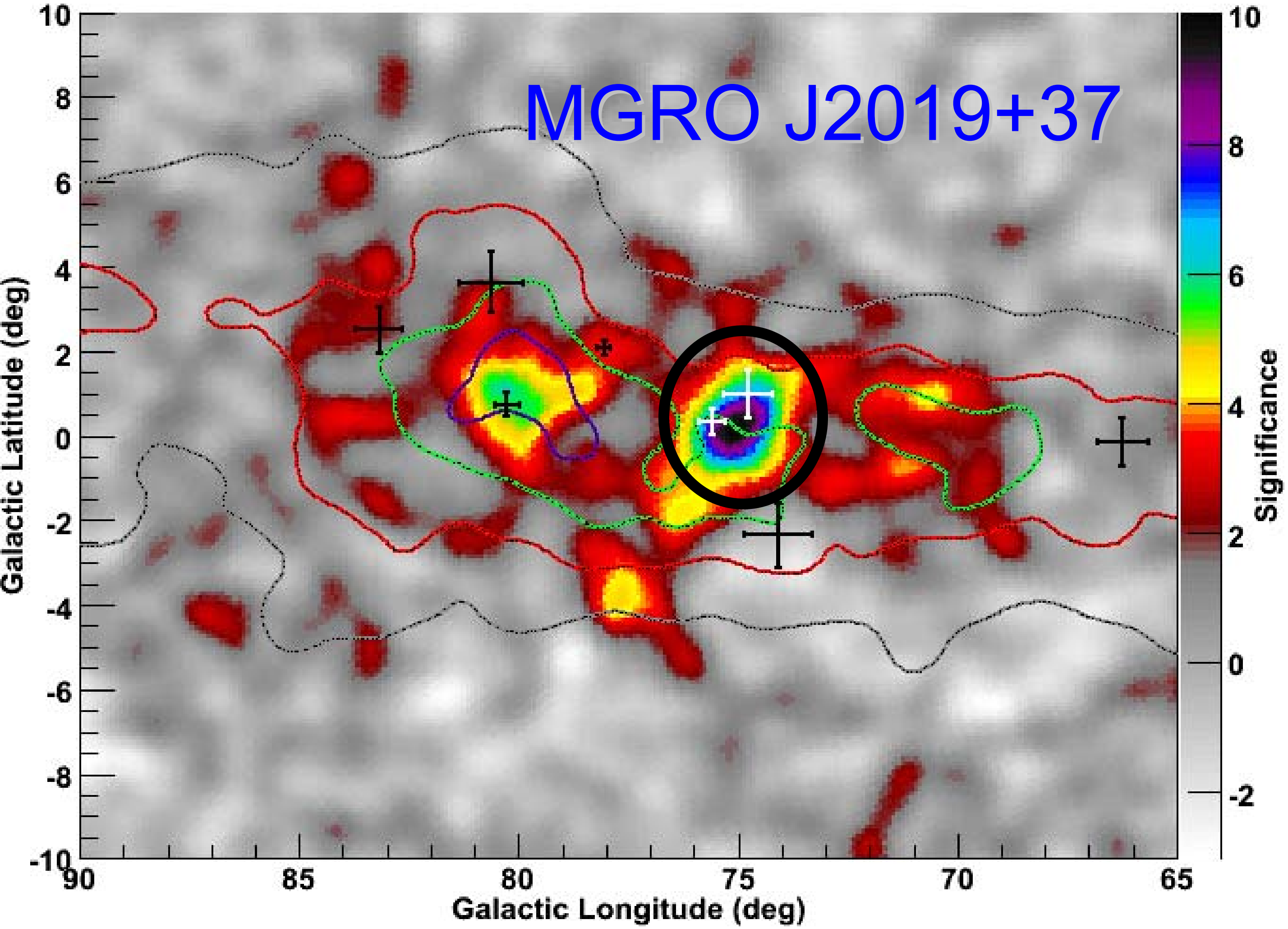
Cygnus Region shows extended excess

$F_{Cygnus} \sim 2 \times F_{crab}$

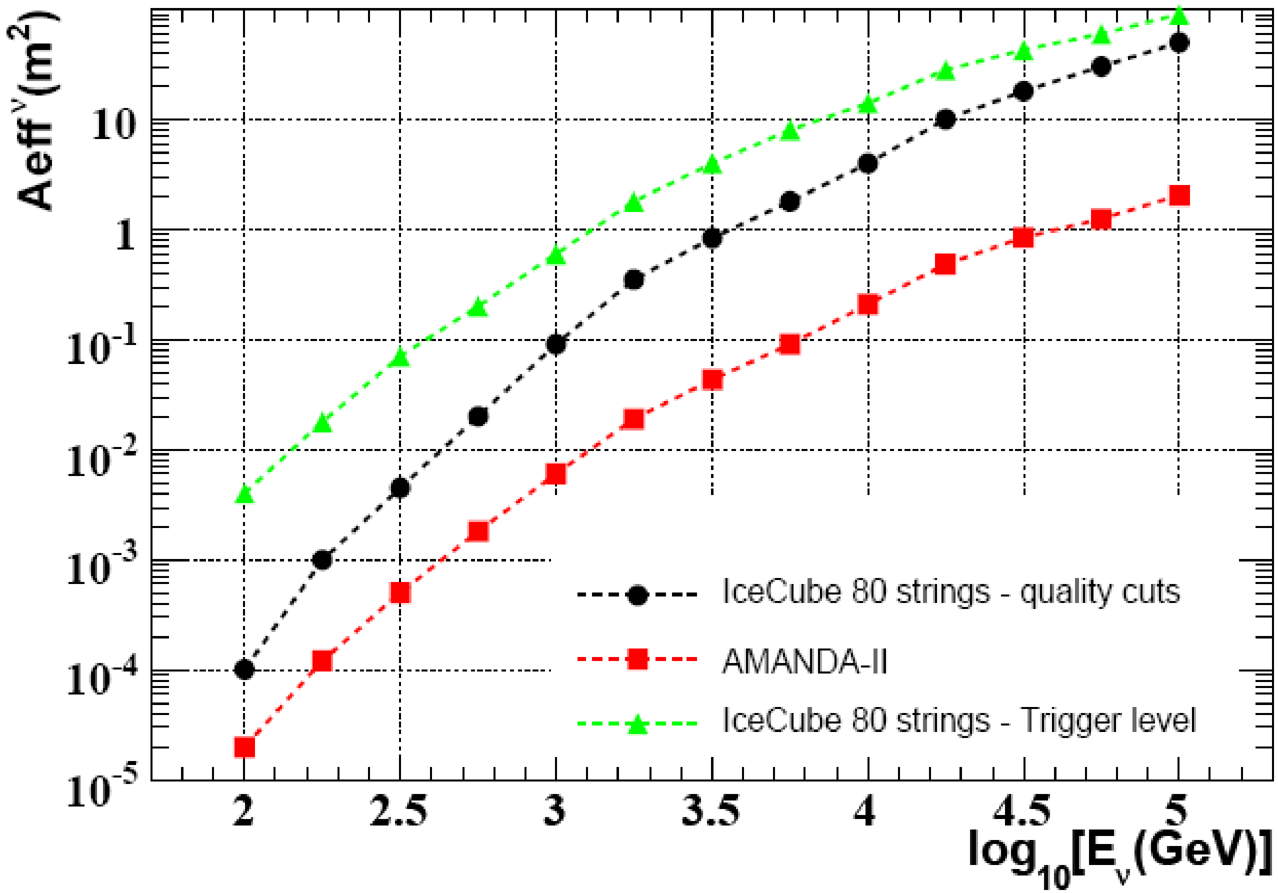
120 square degrees
l (65,85), b (-3,3)

Milagro Data

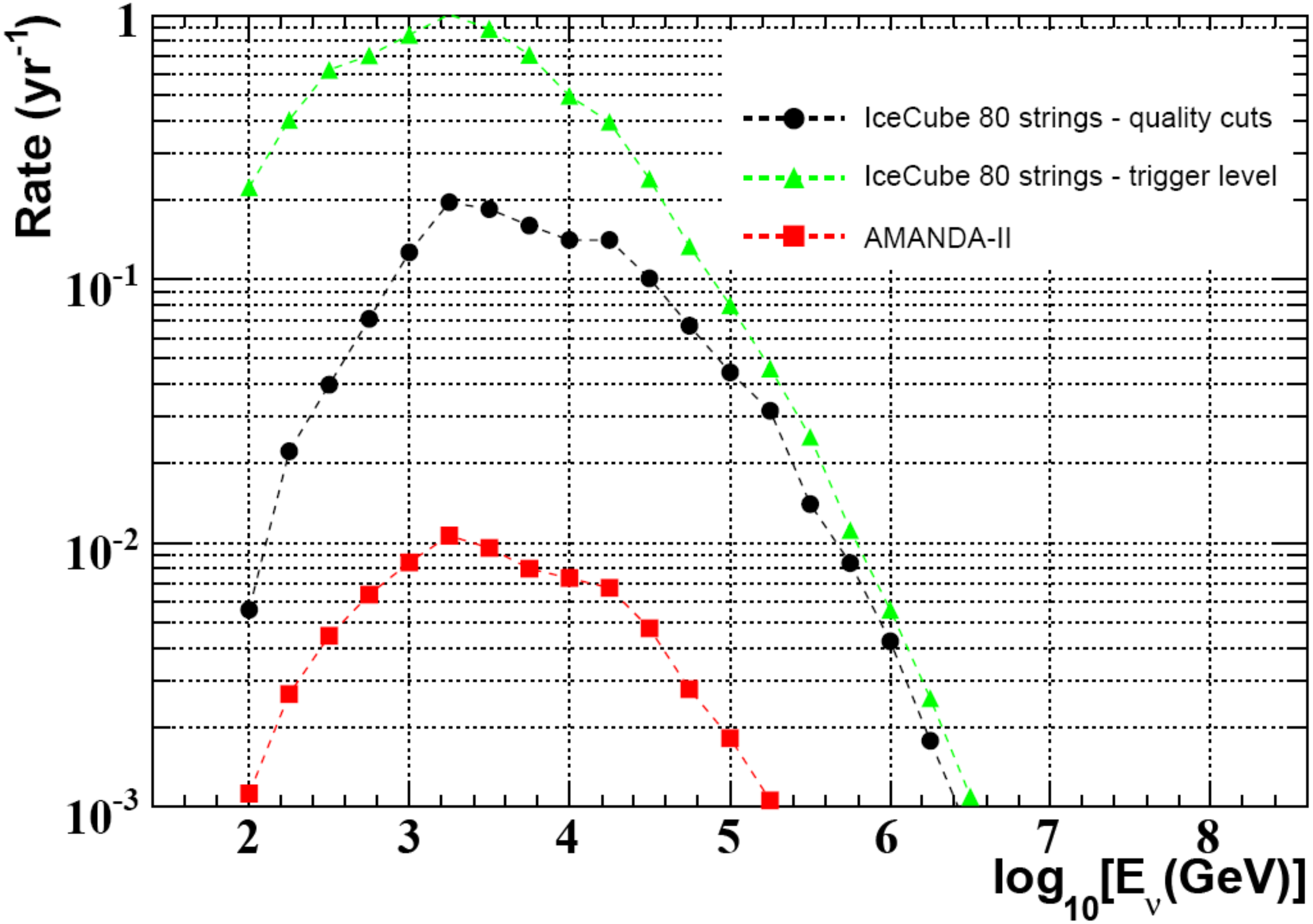
Cygnus Region with Milagro



IceCube/Amanda Effective area



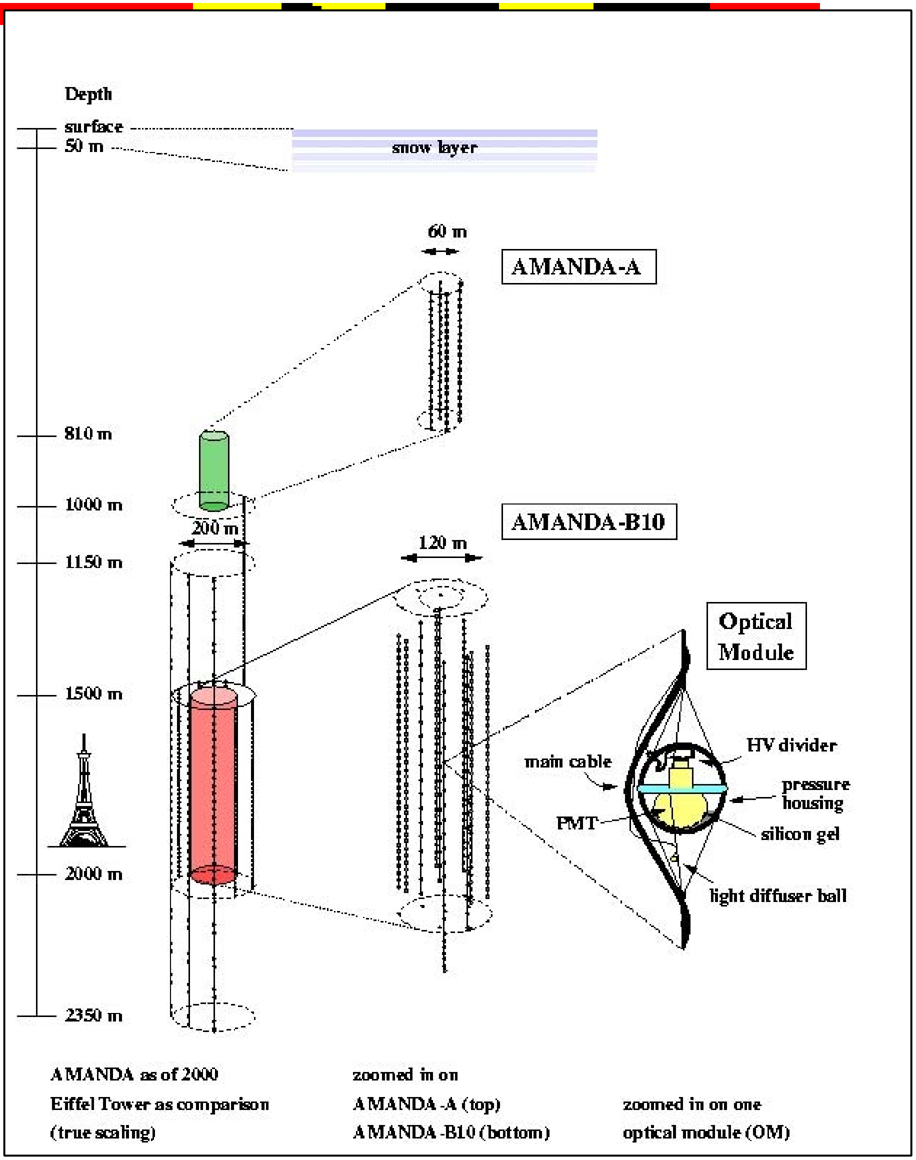
Differential Spectrum MGRO J2019+37



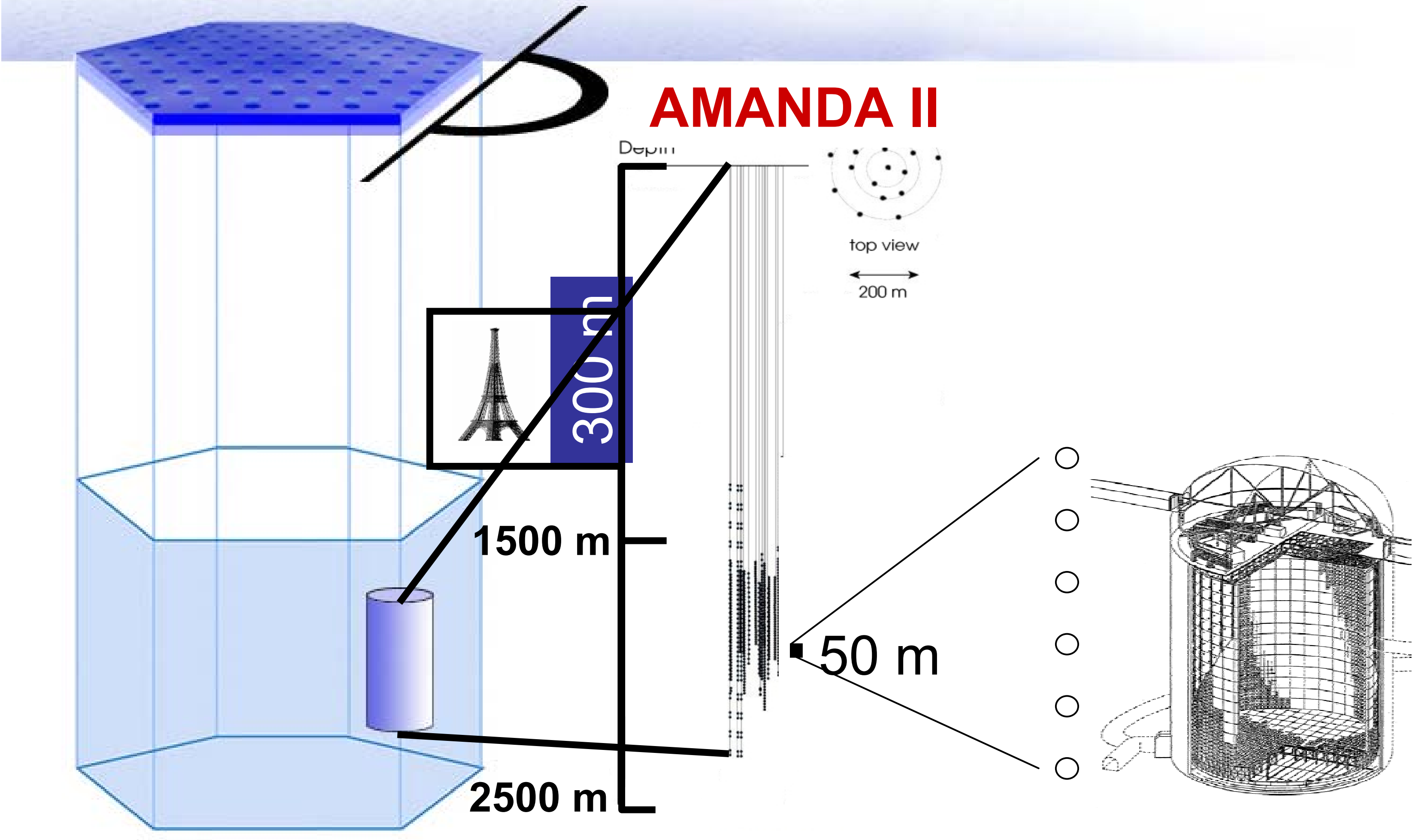
Depending on the spectrum (and if there are protons) IceCube should see this source at 5σ in 2-10 years

AMANDA

- 677 analog OMs deployed along 19 strings
  - 10 strings 1997 (AMANDA B10)
  - 3 strings 1998 (AMANDA B13)
  - 6 strings 2000 (AMANDA II)
- Analog PMT signals using electrical and optical transmission lines.
- 200 m diameter, 500 meters height; AMANDA II encompasses 20 Mton instrumented ice volume.
- AMANDA will remain operational and form IceCube *Inner Core Detector* for low E physics (~ 100 GeV)

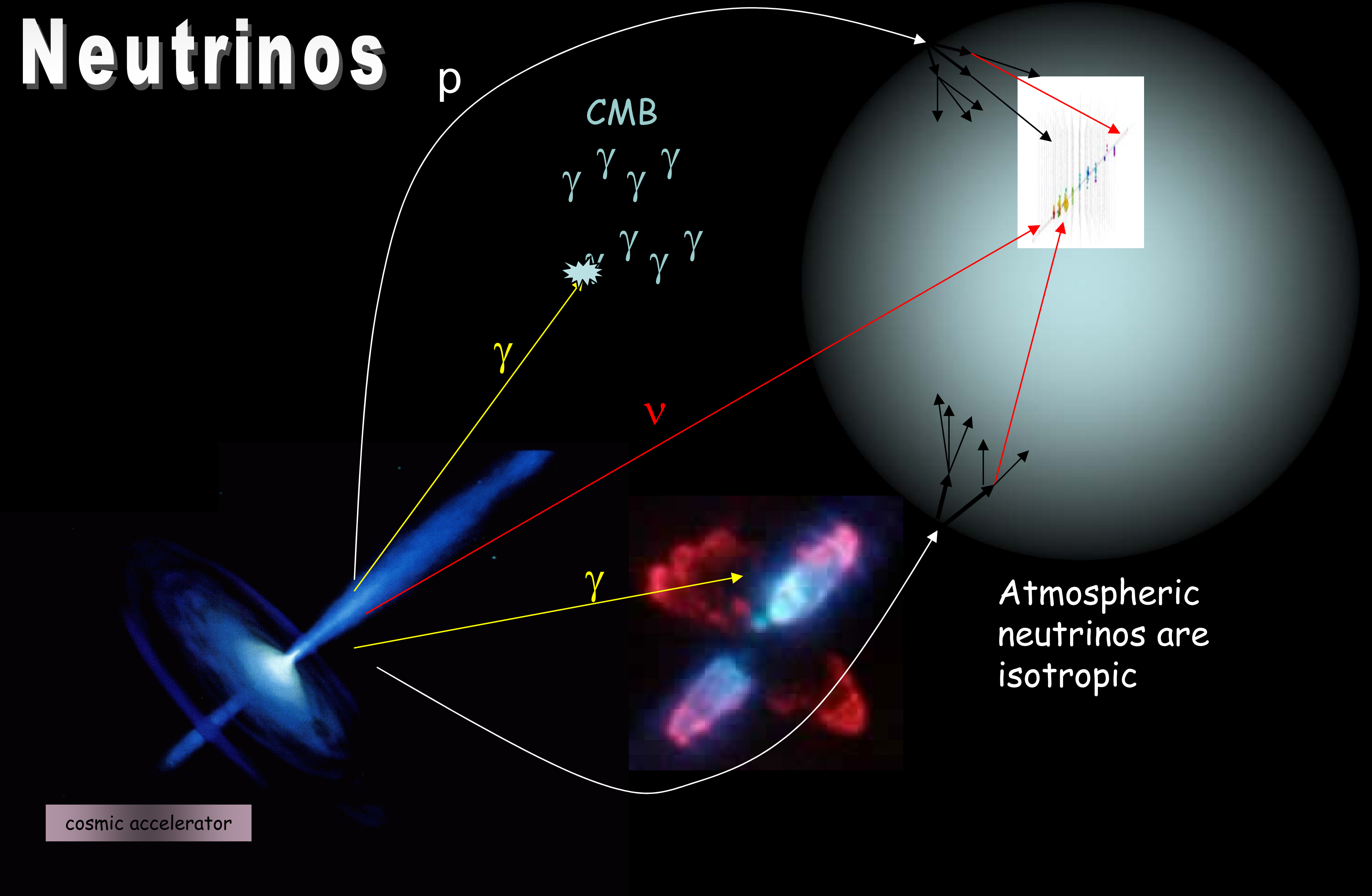


Size Perspective for KM^3

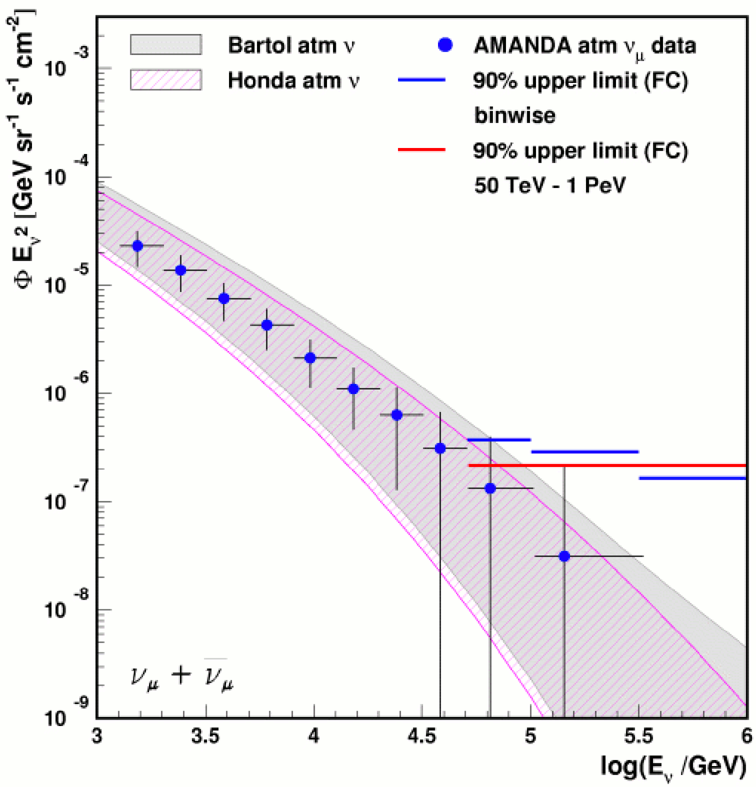


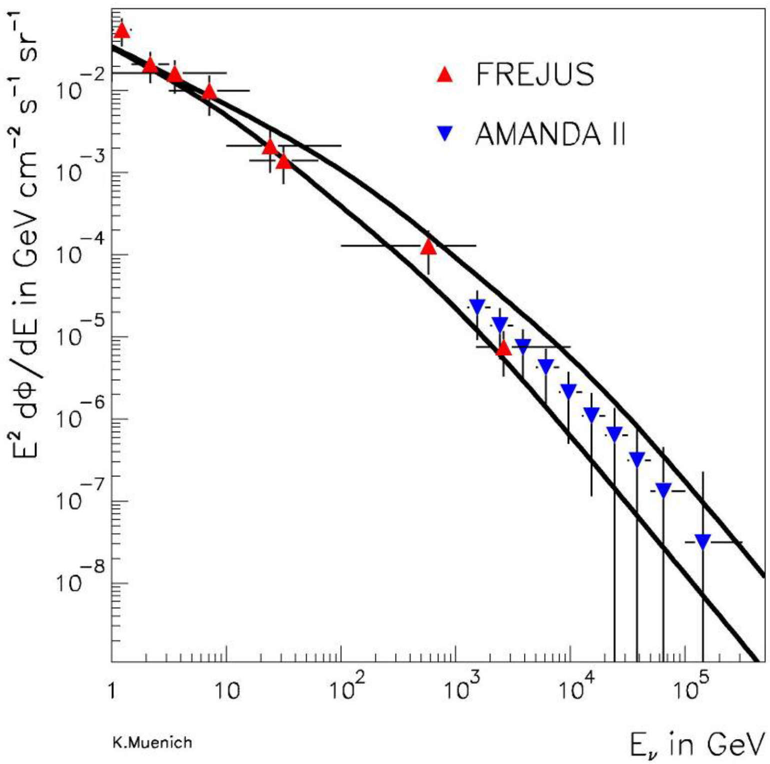
Atmospheric Neutrinos

Atmospheric muons come from above



AMANDA Atmospheric Neutrinos / Diffuse Flux

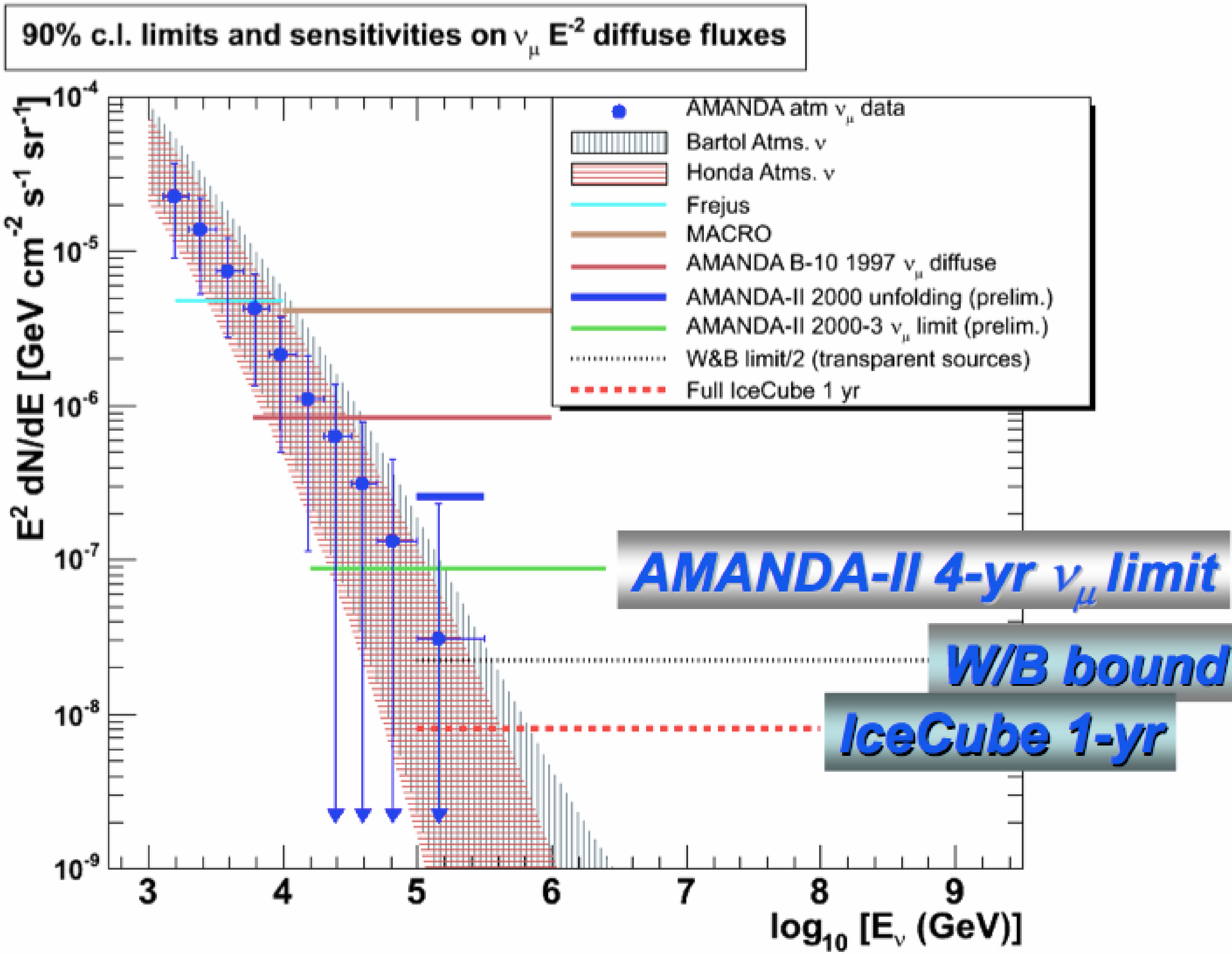




Limit on diffuse E^{-2} ν_μ flux (100-300 TeV):

$$E^2\Phi_{\nu_\mu}(E) < 2.6\cdot10^{-7}\ \mathrm{GeV\ cm^{-2}\ s^{-1}\ sr^{-1}}$$

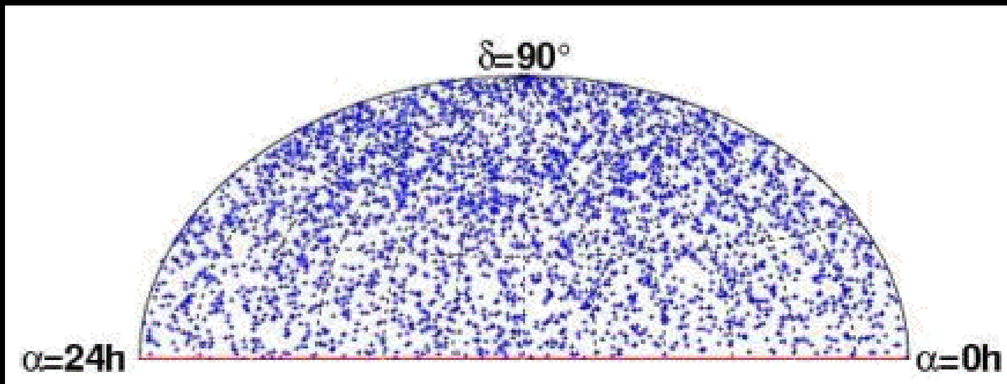
Includes 33% systematic uncertainty



90% c.l. limits and sensitivities on ν_μ E^{-2} diffuse fluxes
E^2 dN/dE [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
3
4
5
6
7
8
9
$\log_{10}$ [E_ν (GeV)]
AMANDA atm ν_μ data
Bartol Atms. ν
Honda Atms. ν
Frejus
MACRO
AMANDA B-10 1997 ν_μ diffuse
AMANDA-II 2000 unfolding (prelim.)
AMANDA-II 2000-3 ν_μ limit (prelim.)
W&B limit/2 (transparent sources)
Full IceCube 1 yr
AMANDA-II 4-yr ν_μ limit
W/B bound
IceCube 1-yr

AMANDA Point Source Search

IceCube looks at the Northern sky

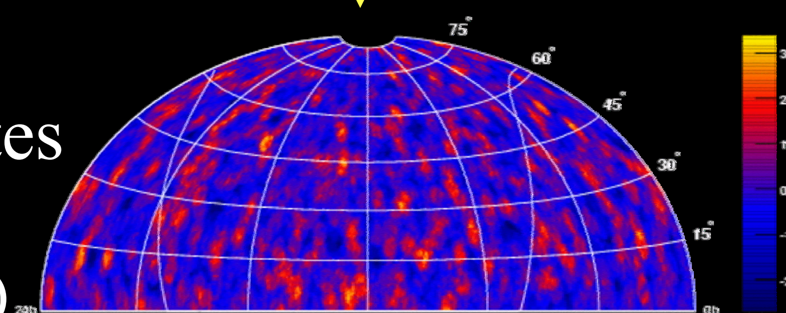


AMANDA 2000-2003

- 3329 ν_μ events
- 95% purity

Significance plot

- Highest excess ~3.4σ
- Probability 92%



Search 33 ν source candidates

- Crab Nebula
  - 10 events (5.4 bkgnd ~1.7σ)
  - Probability background fluctuation 64%

No evidence for extraterrestrial point sources

Candidate Amanda Sources

Source	Events observed/ background (5 years)	Events observed/ background (4 years)	Flux upper limit Sys. unc. 15% sig, 8% bg $\Phi_{90\%}(E_\nu > 10\ \mathrm{GeV})\ [10^{-8} cm^{-2} s^{-1}]$ (5 years)
Markarian 421	6 / 7.37	6 / 5.58	0.43
Markarian 501	8 / 6.39	5 / 4.96	0.85
1ES1959+650	5 / 4.77	5 / 3.71	0.78
M87	6 / 6.08	4 / 4.90	0.50
3C273	8 / 4.72		0.99
SS433	4 / 6.14	2 / 4.50	0.27
CI Cam	9 / 6.72	5 / 5.11	1.04
Cygnus X-1	8 / 7.01	4 / 5.21	0.76
Cygnus X-3	7 / 6.48	6 / 5.04	0.67
Crab Nebula	10 / 6.74	10 / 5.36	1.01

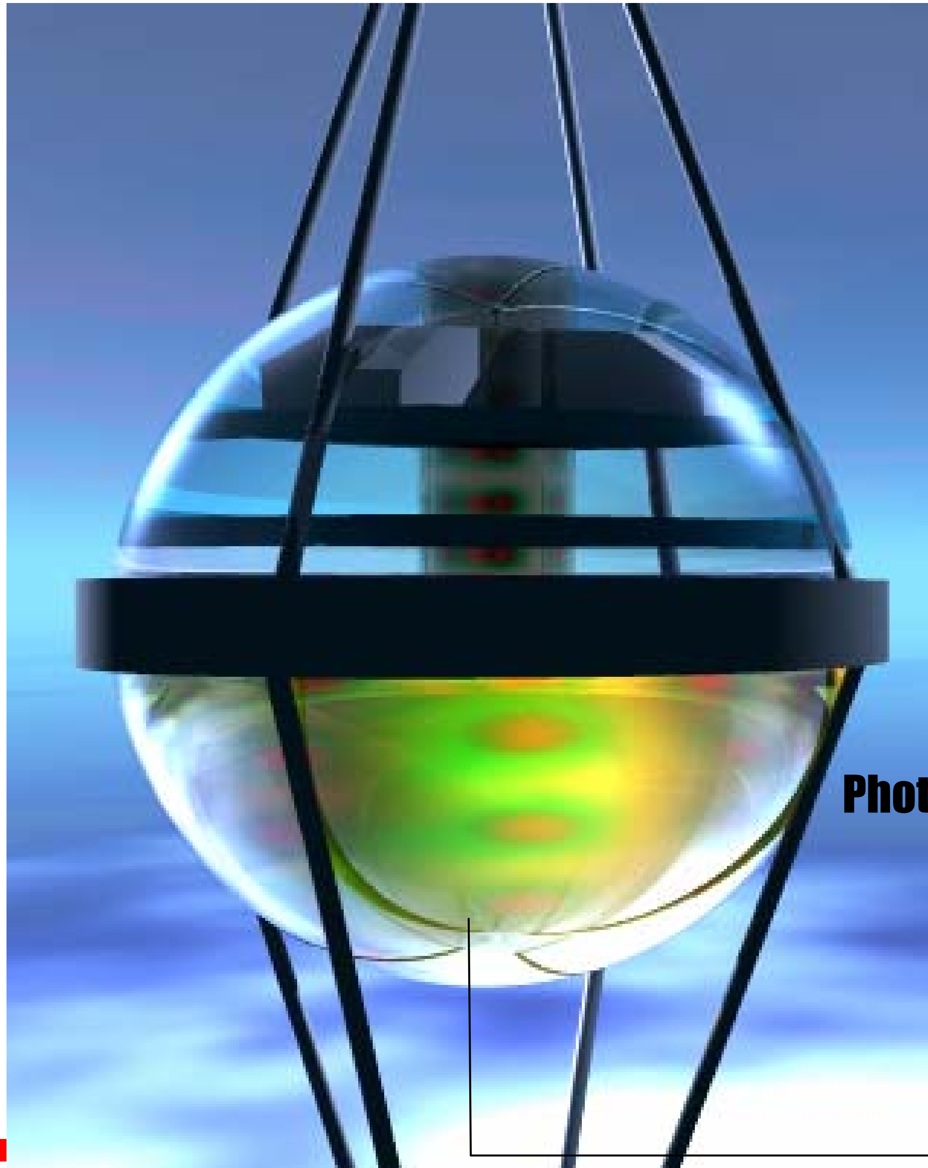
- **No significant excess**, no indication for a neutrino source
- No new events seen from the direction of Crab Nebula

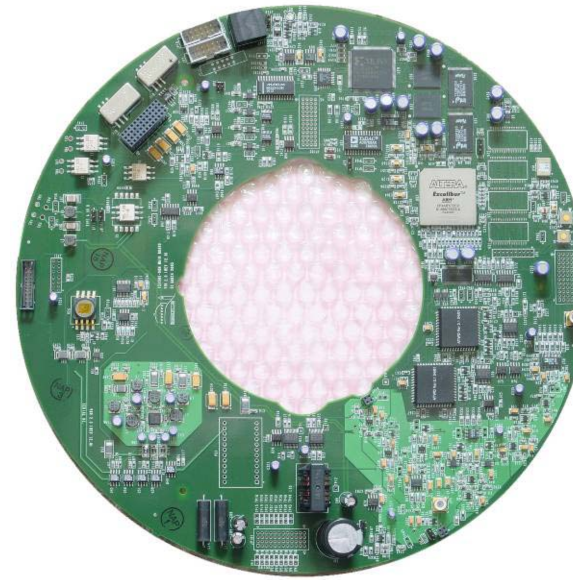
IceCube

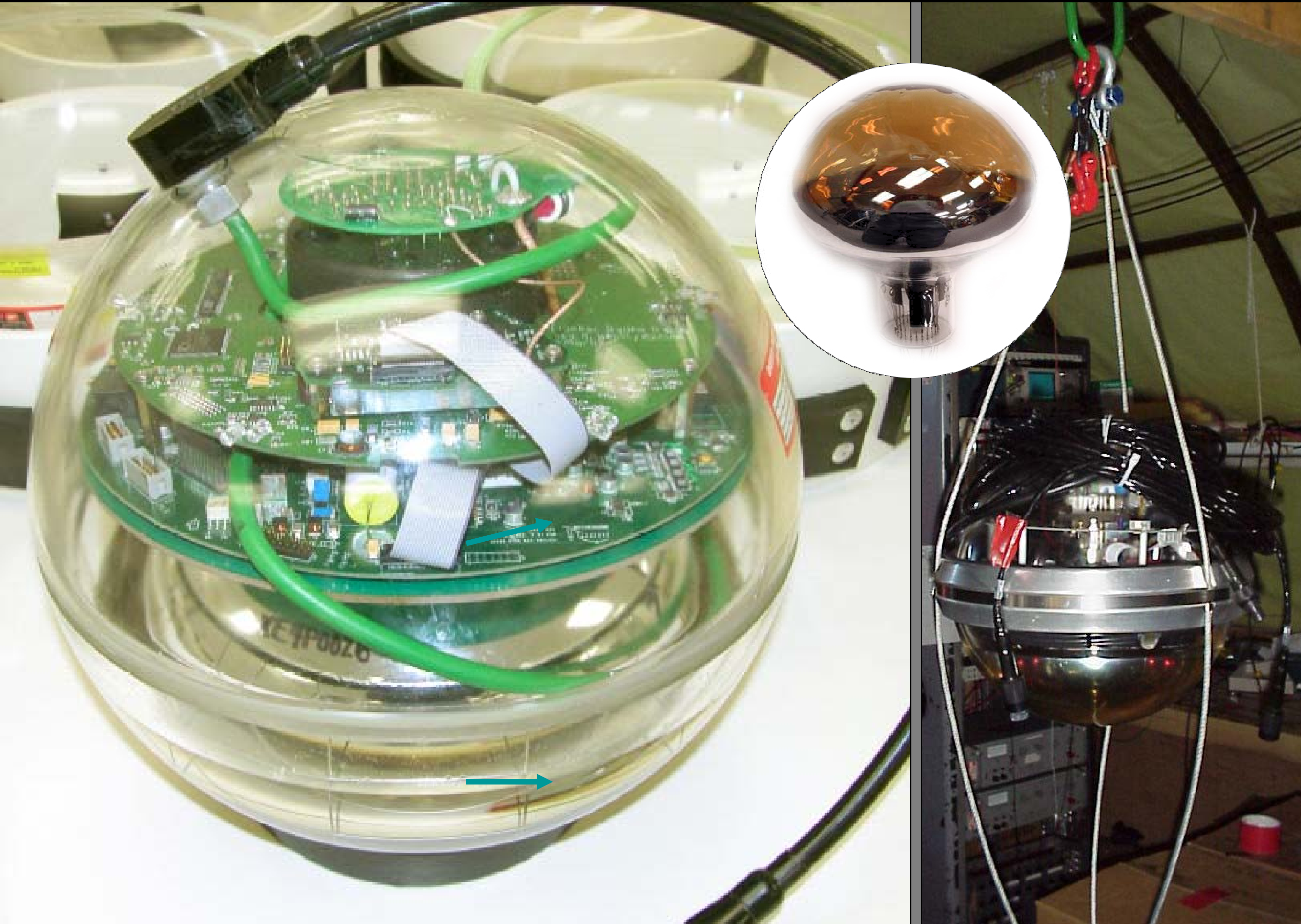
South Pole


IceCube
South Pole Station
AMANDA
Skiway
Geographic
South Pole
Dark sector

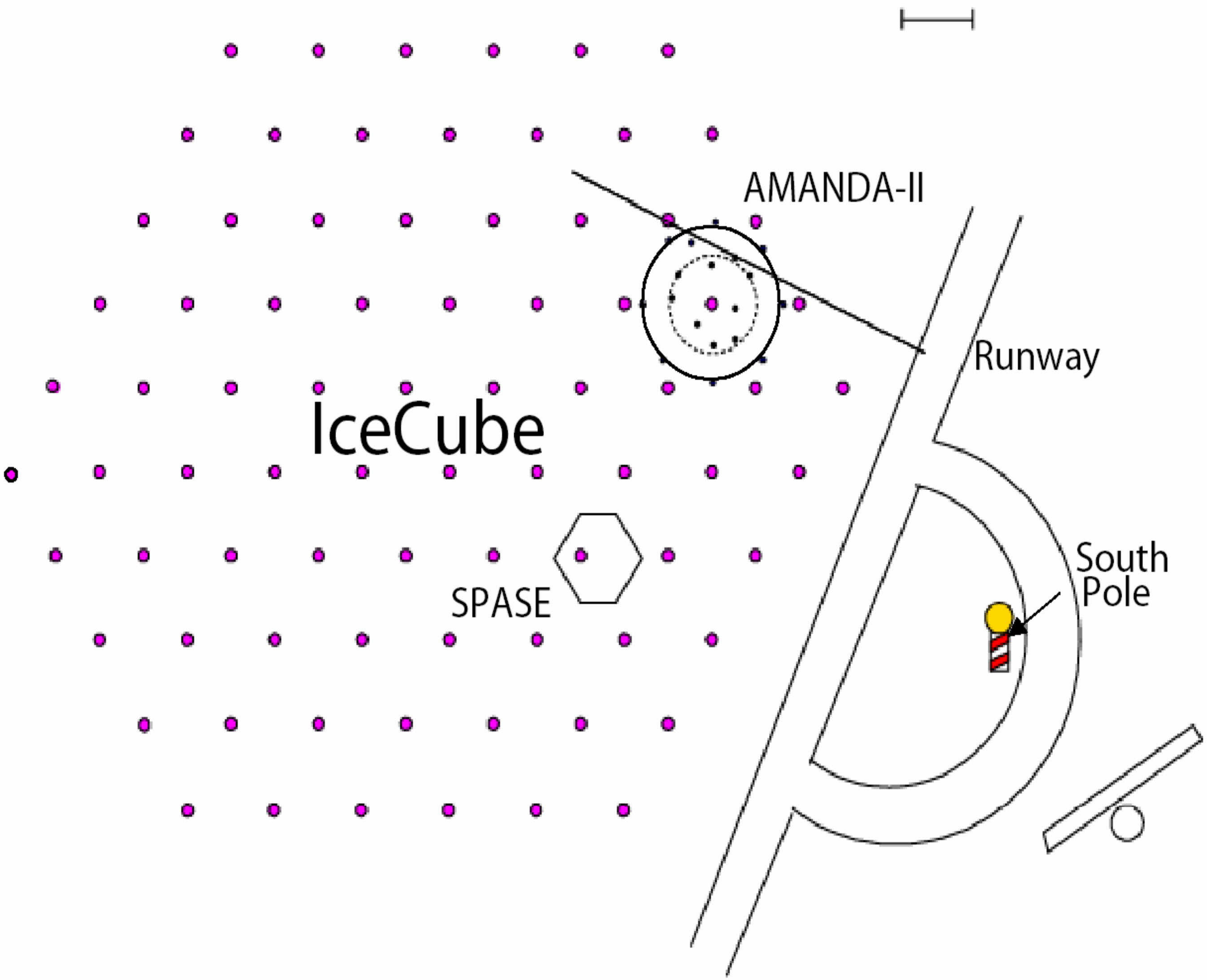
IceCube Digital Optical Module



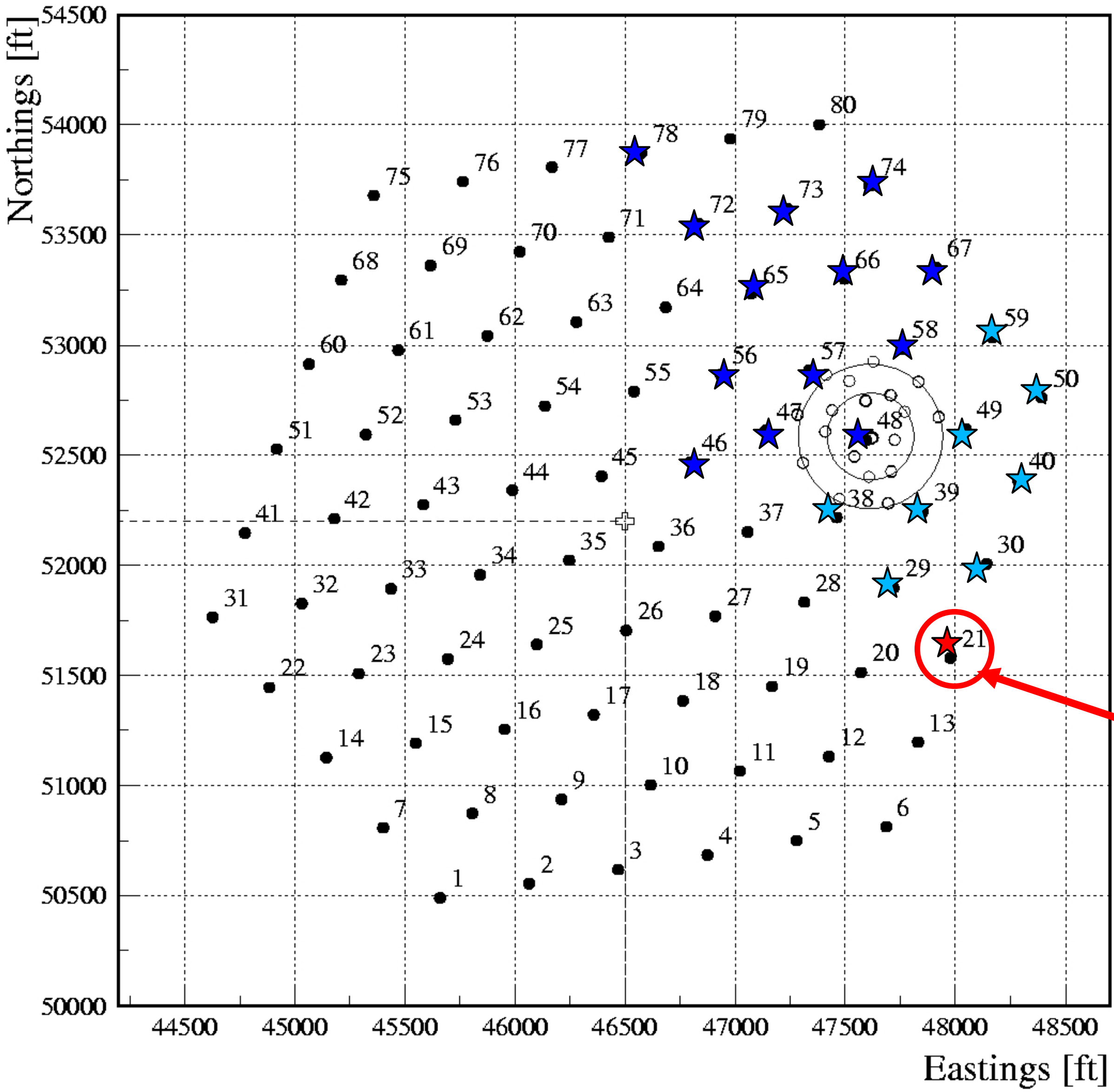




Ice Cube



2005, 2006, 2007 Deployments

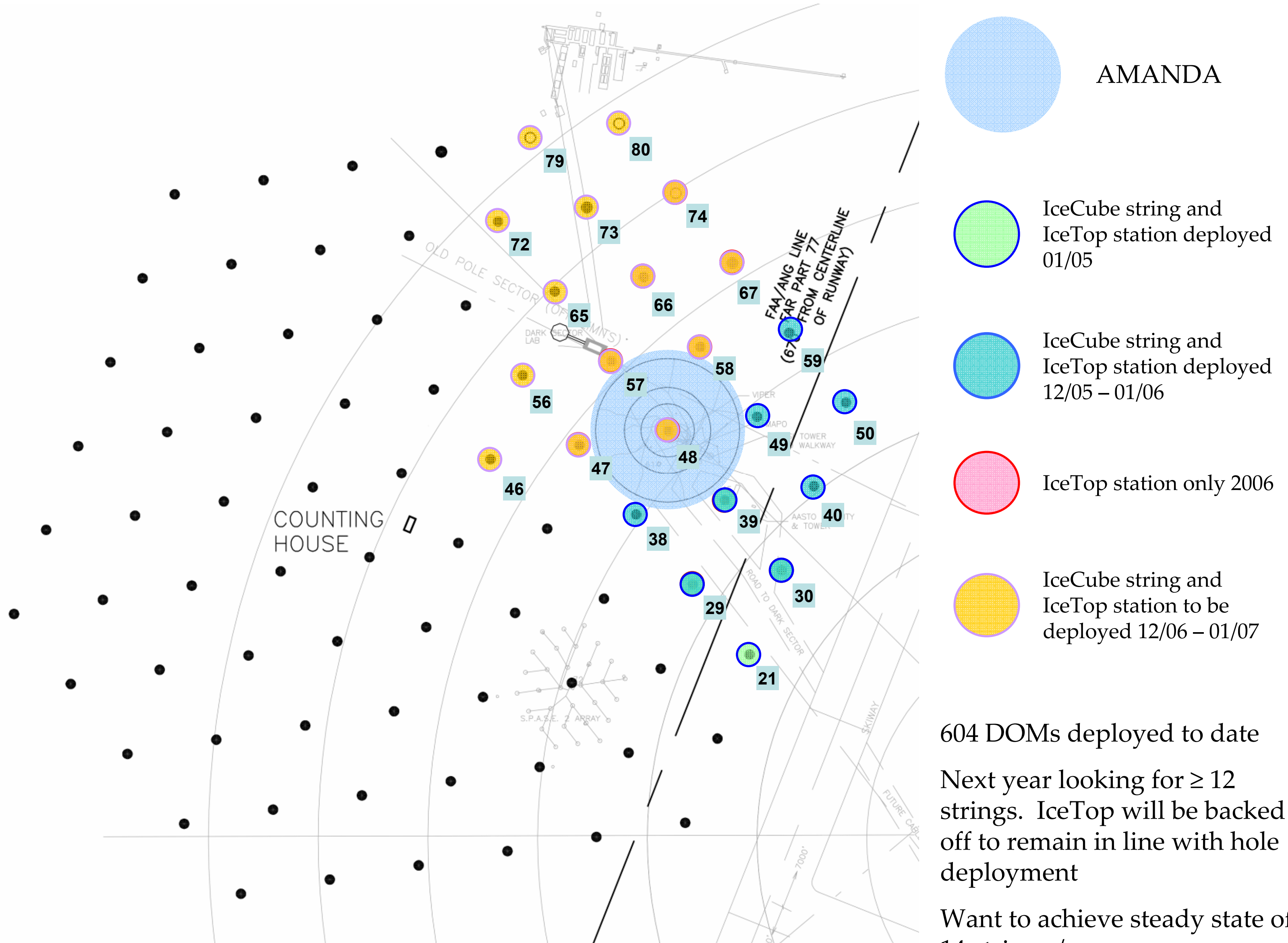


installed in 06-07

installed in 05-06

First string January 27, 2005!

2005, 2006, 2007 Deployments

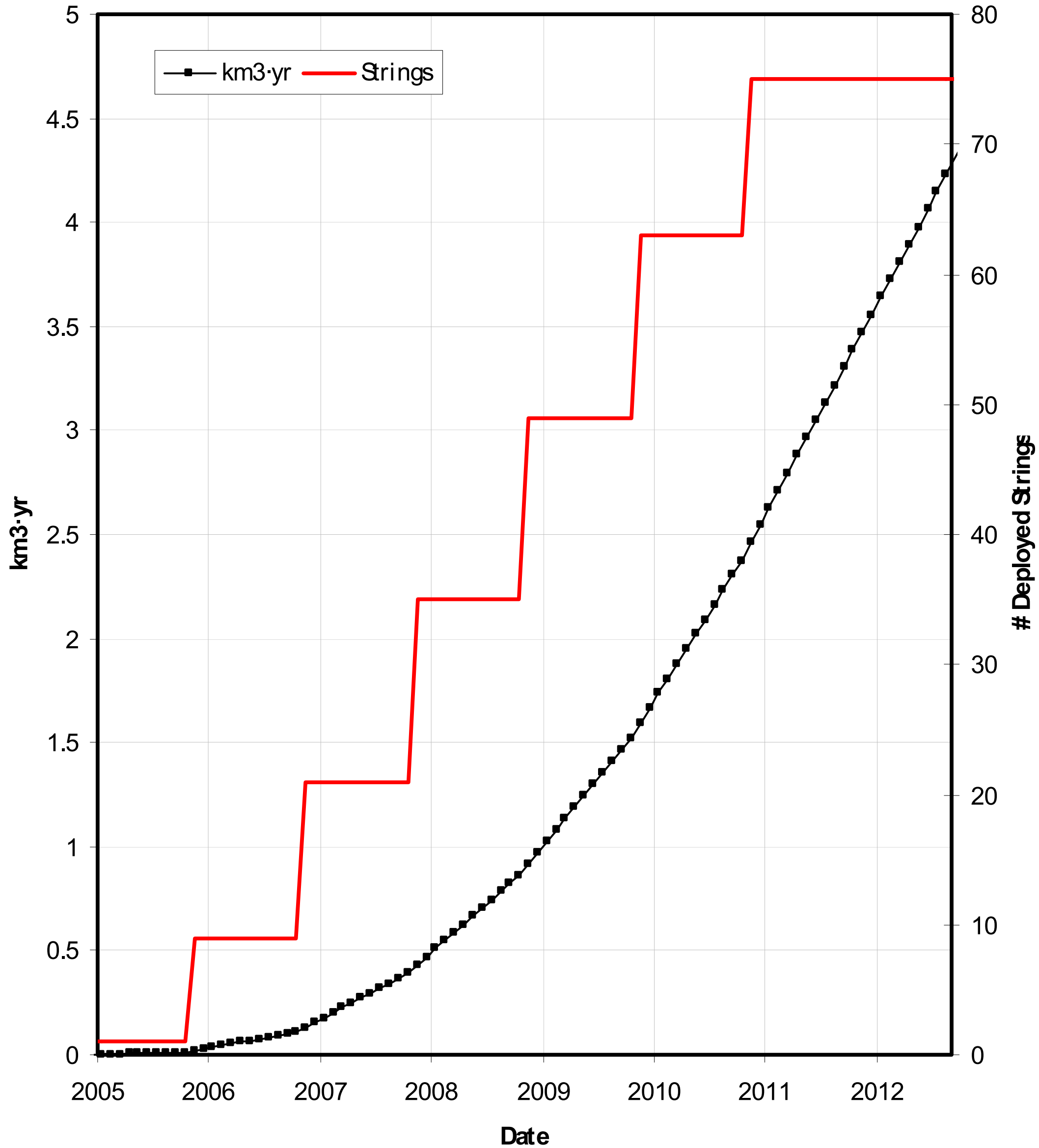


604 DOMs deployed to date

Next year looking for ≥ 12 strings. IceTop will be backed off to remain in line with hole deployment

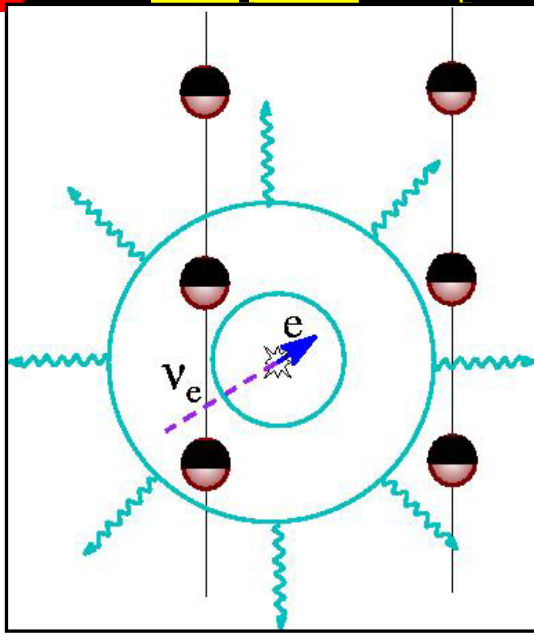
Want to achieve steady state of 14 strings/season.

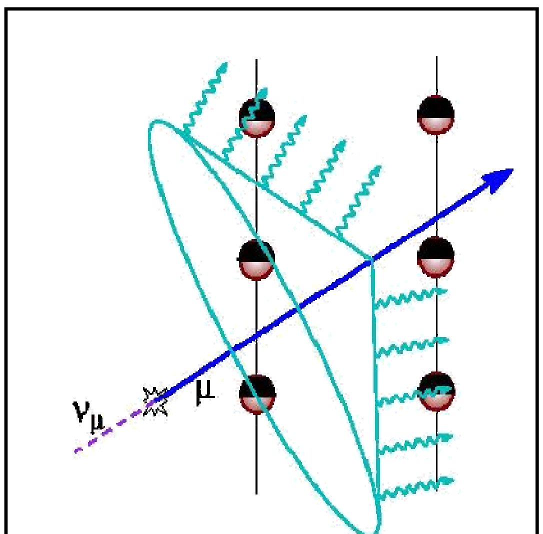
IceCube Integrated Volume (Projected)

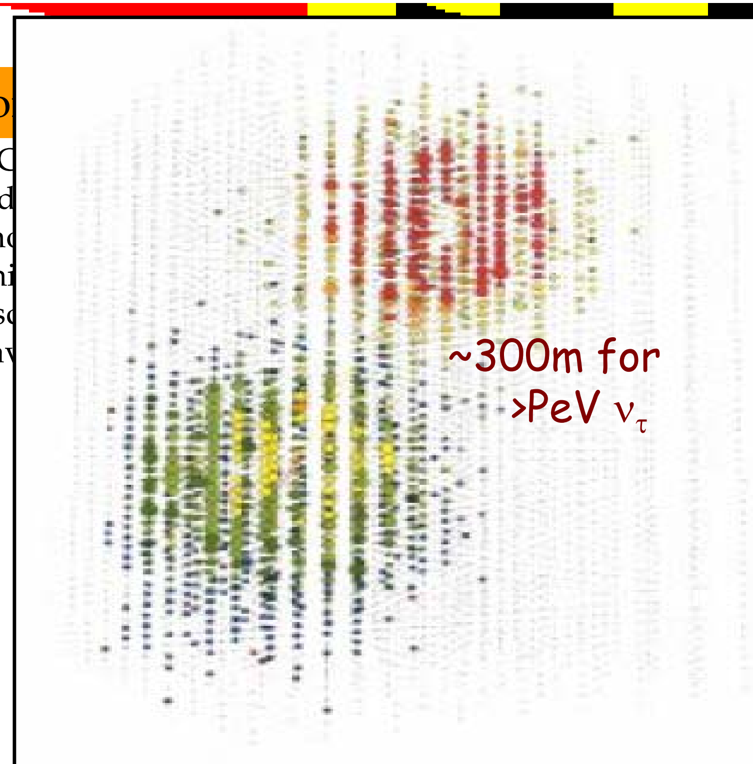


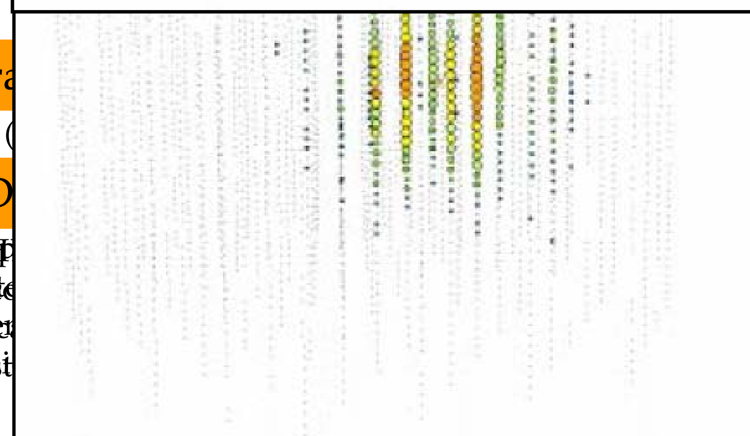
- # of strings per year is based on latest "best guess" deployment rate of 12 strings this year and 14 strings per season thereafter.
- 1 km^3·yr reached 2 years *before* detector is completed
- Close to 4 km^3·yr at the beginning of 2^{nd} year of full array operation.

Finding neutrinos in the ice



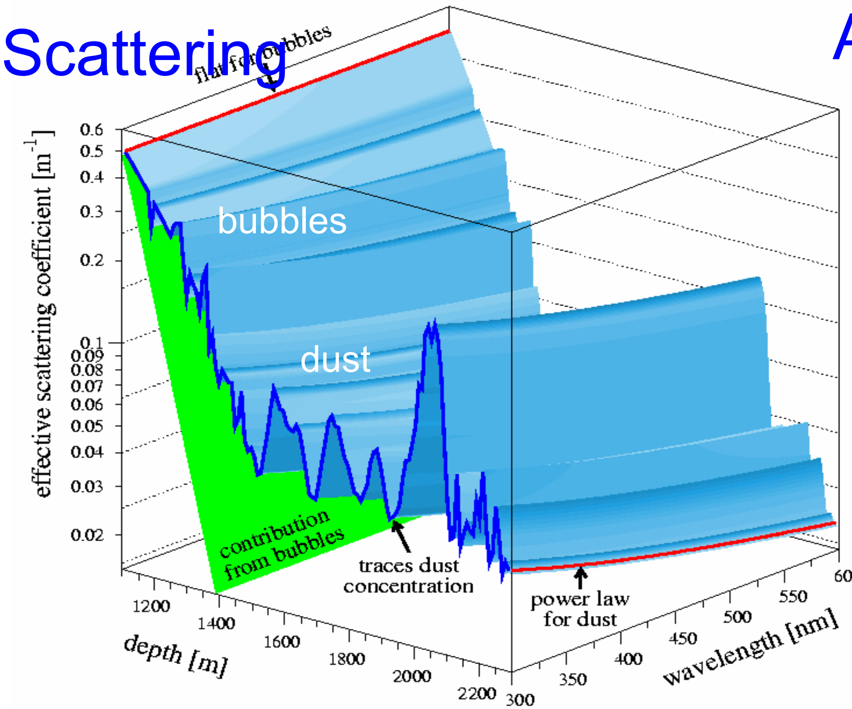




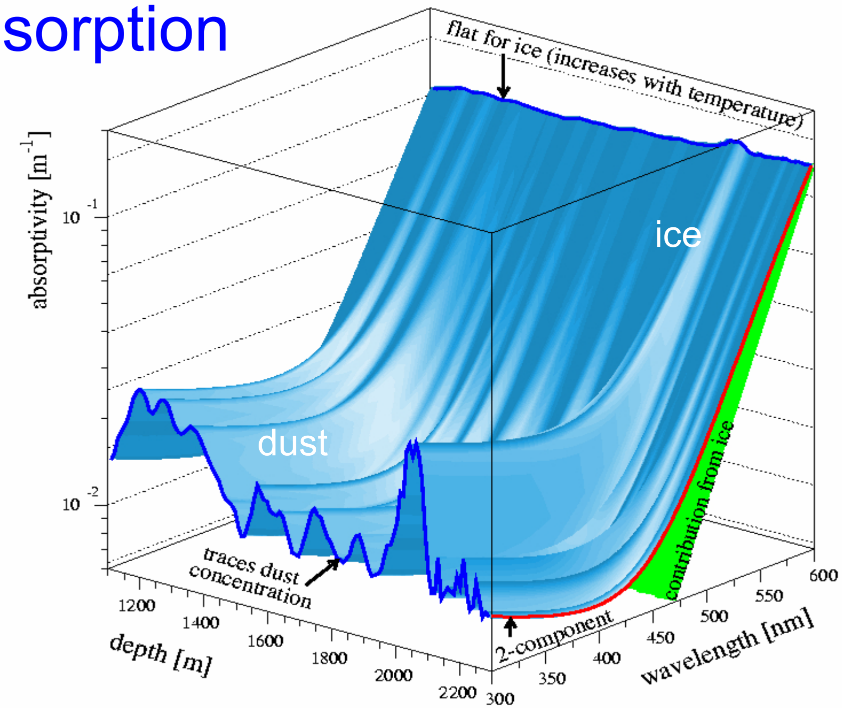


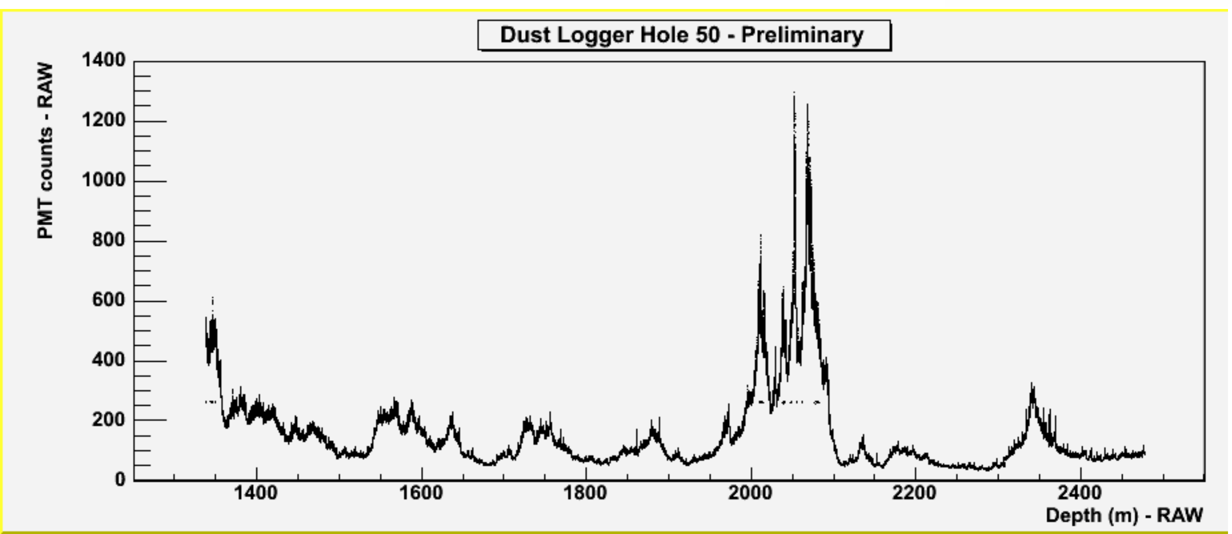
Ice Properties

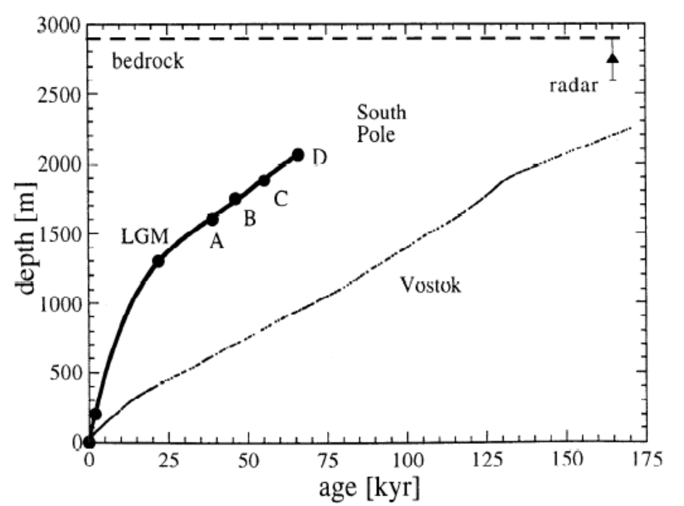
Scattering



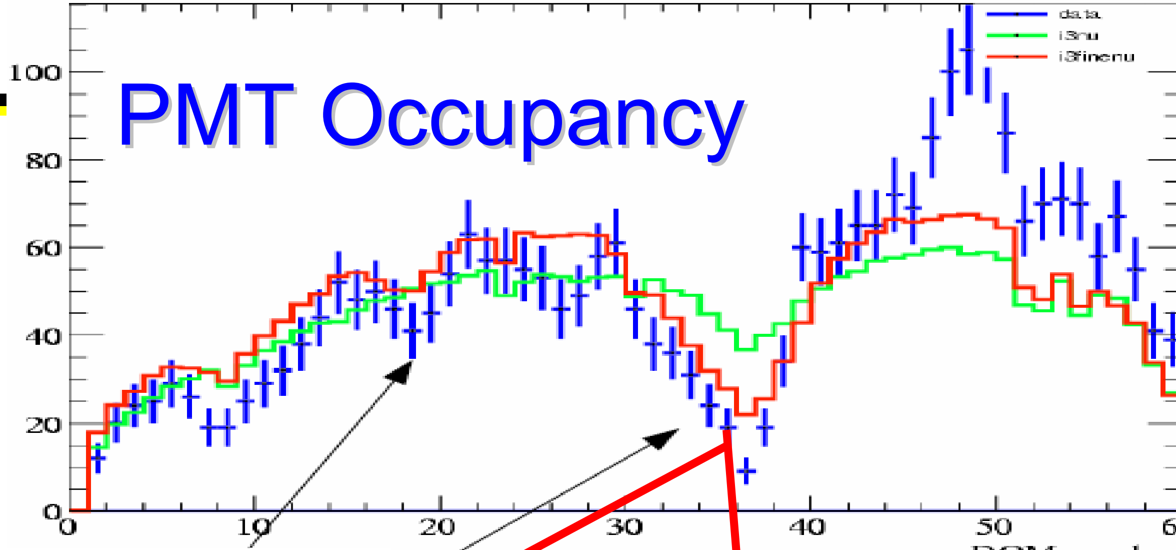
Absorption



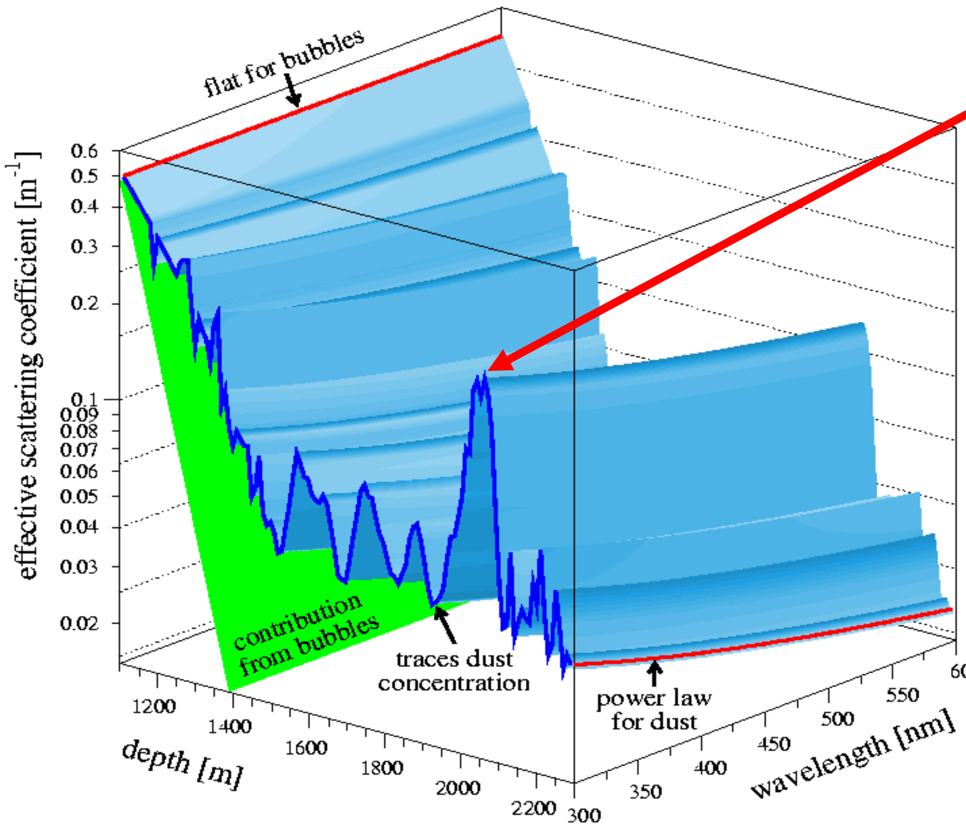


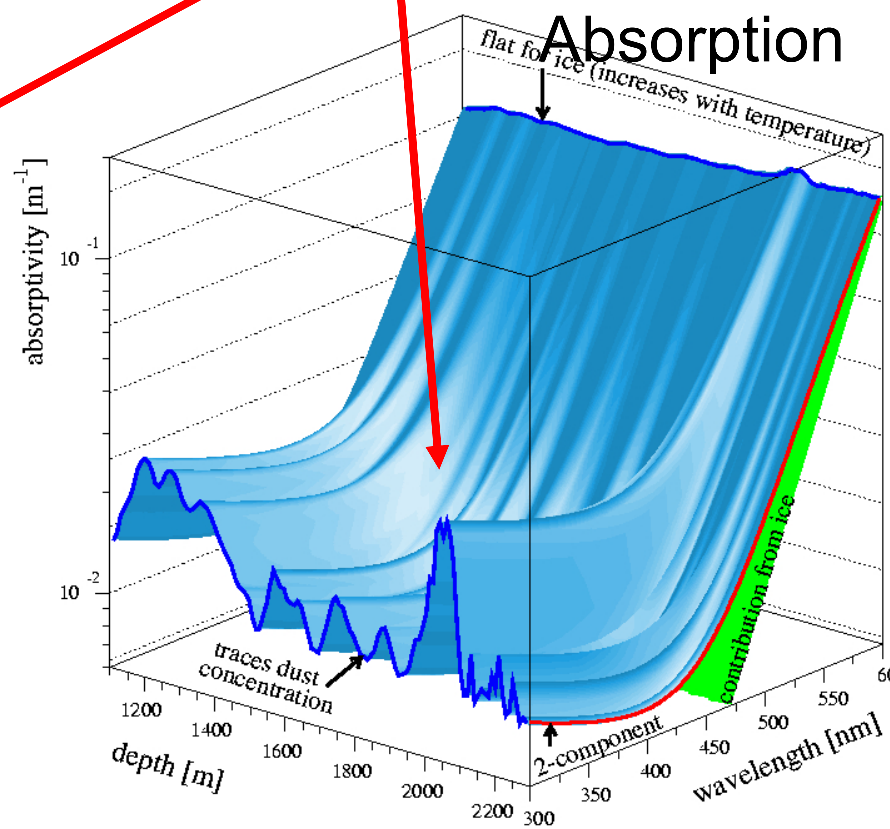


Effects of Ice Properties



Scattering

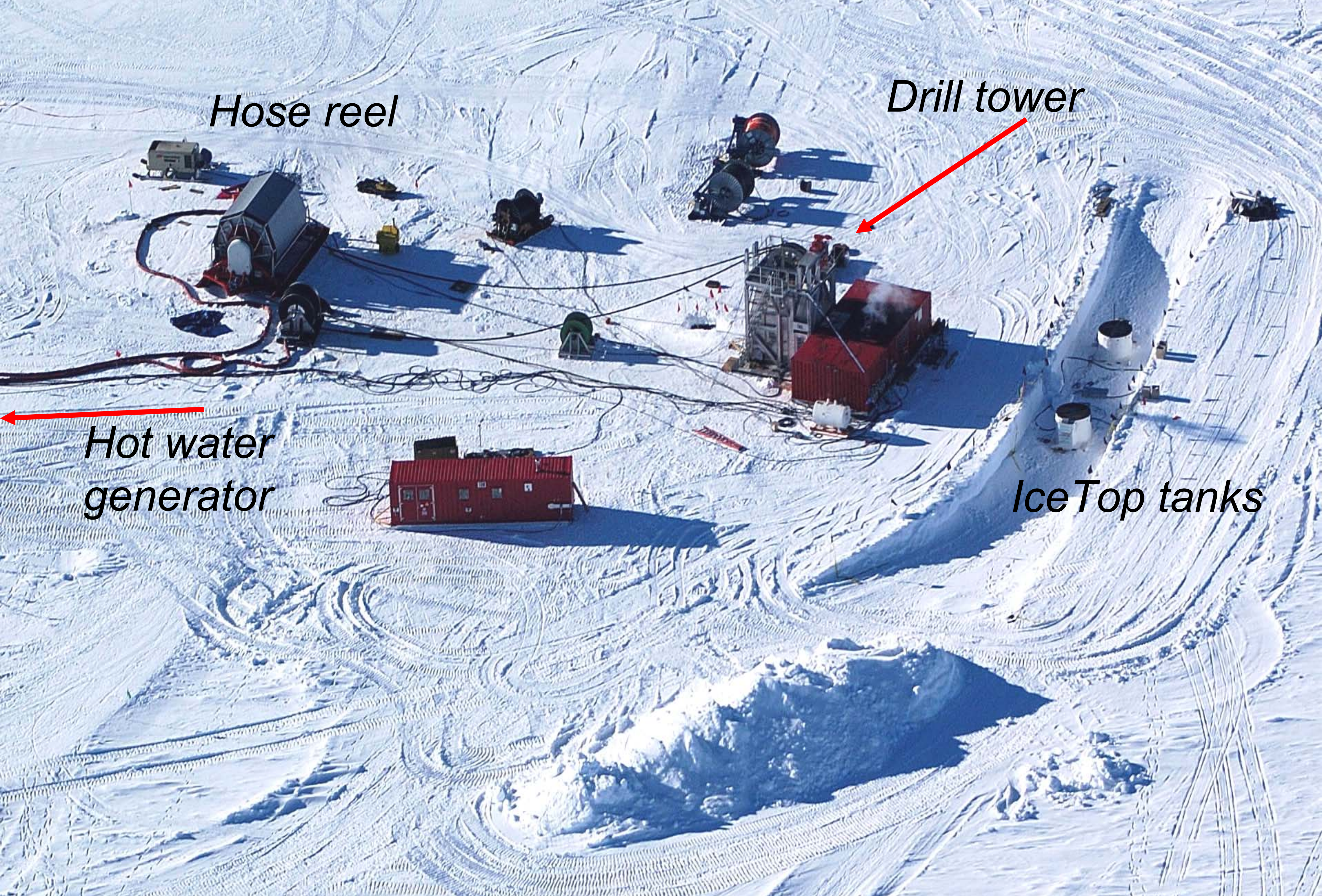




Building it

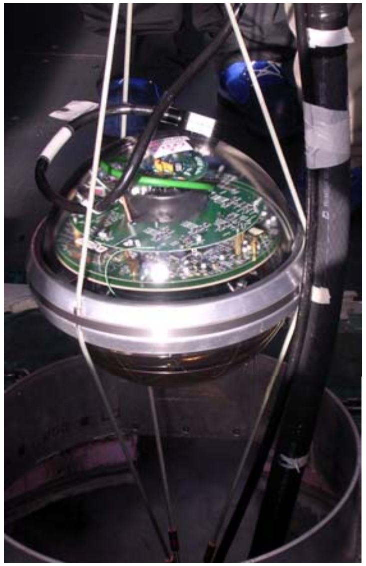
drill made of a hose with hot water

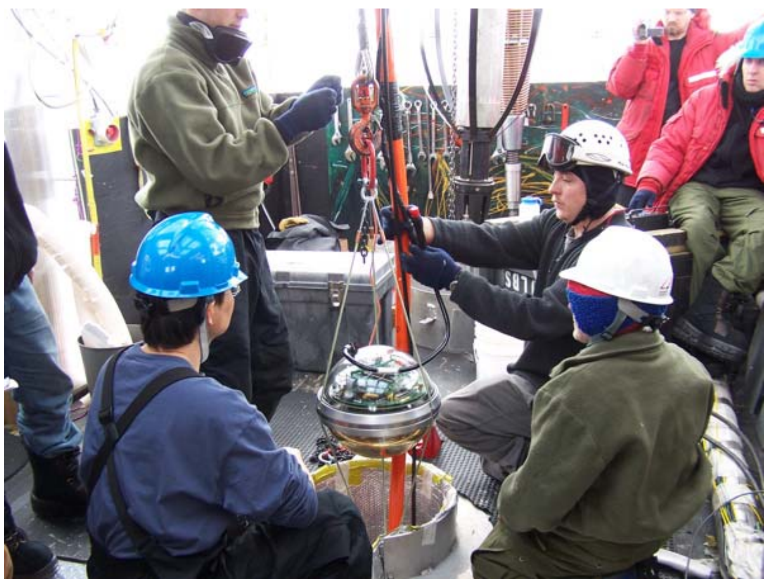
the spool to roll up miles of hose

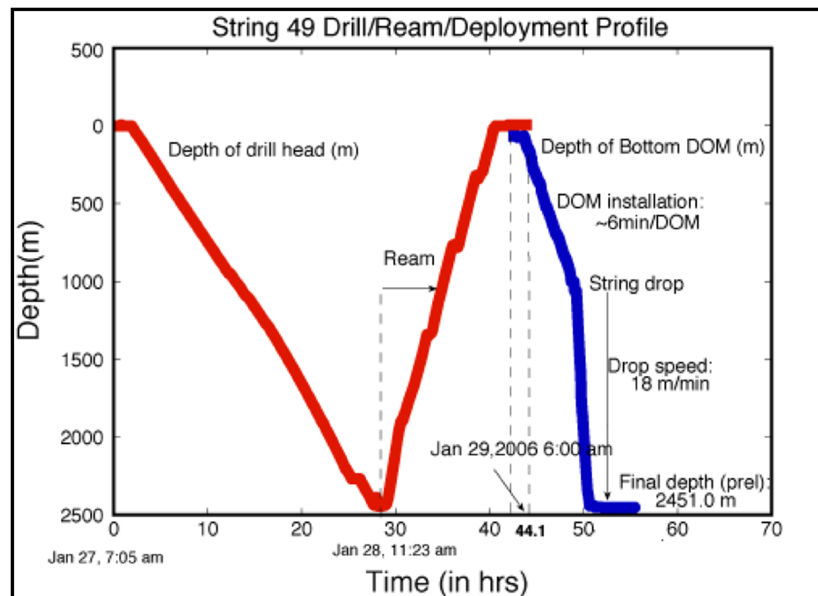


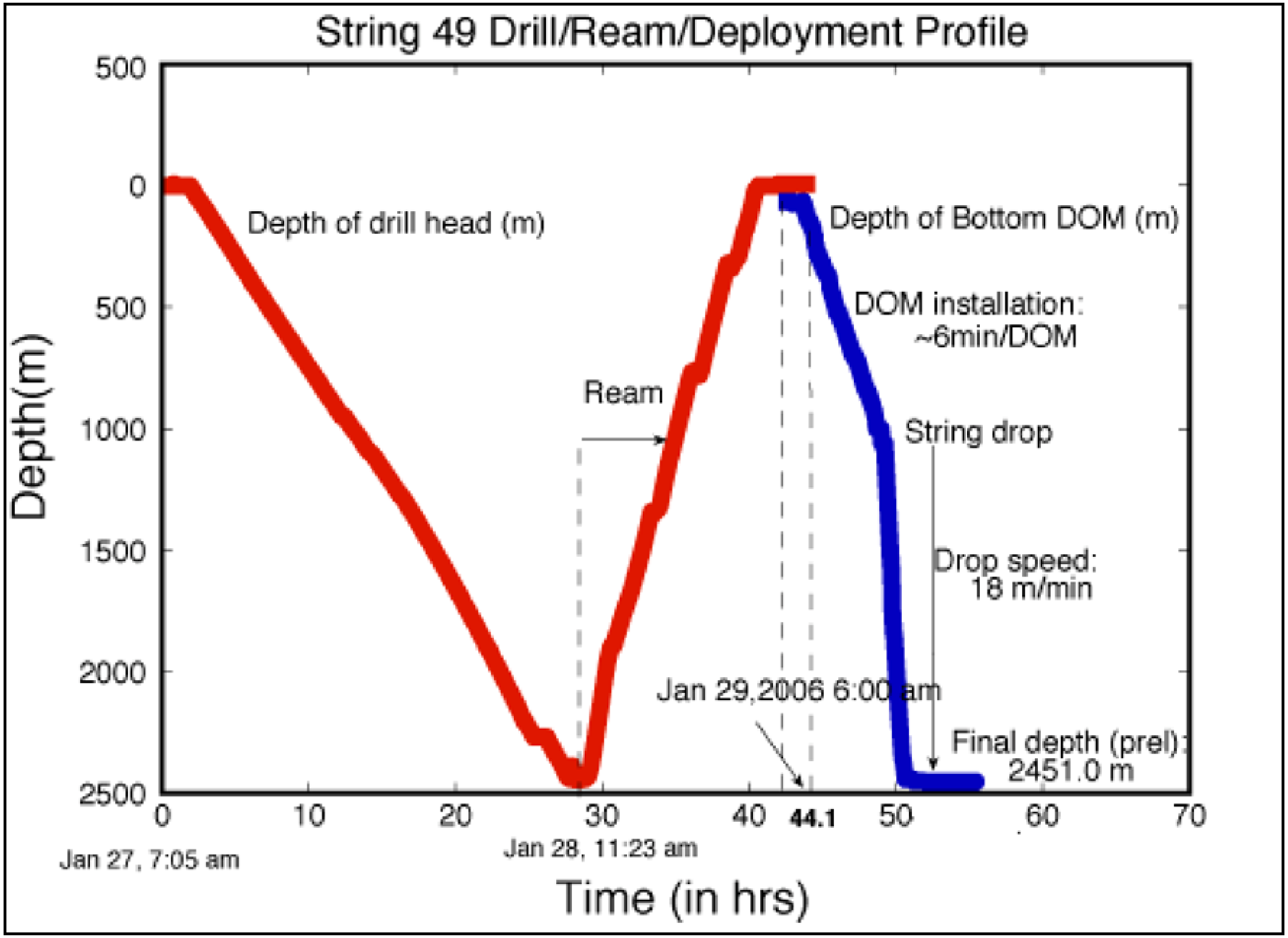
The drilling site in January, 2005

Drilling and Deployment



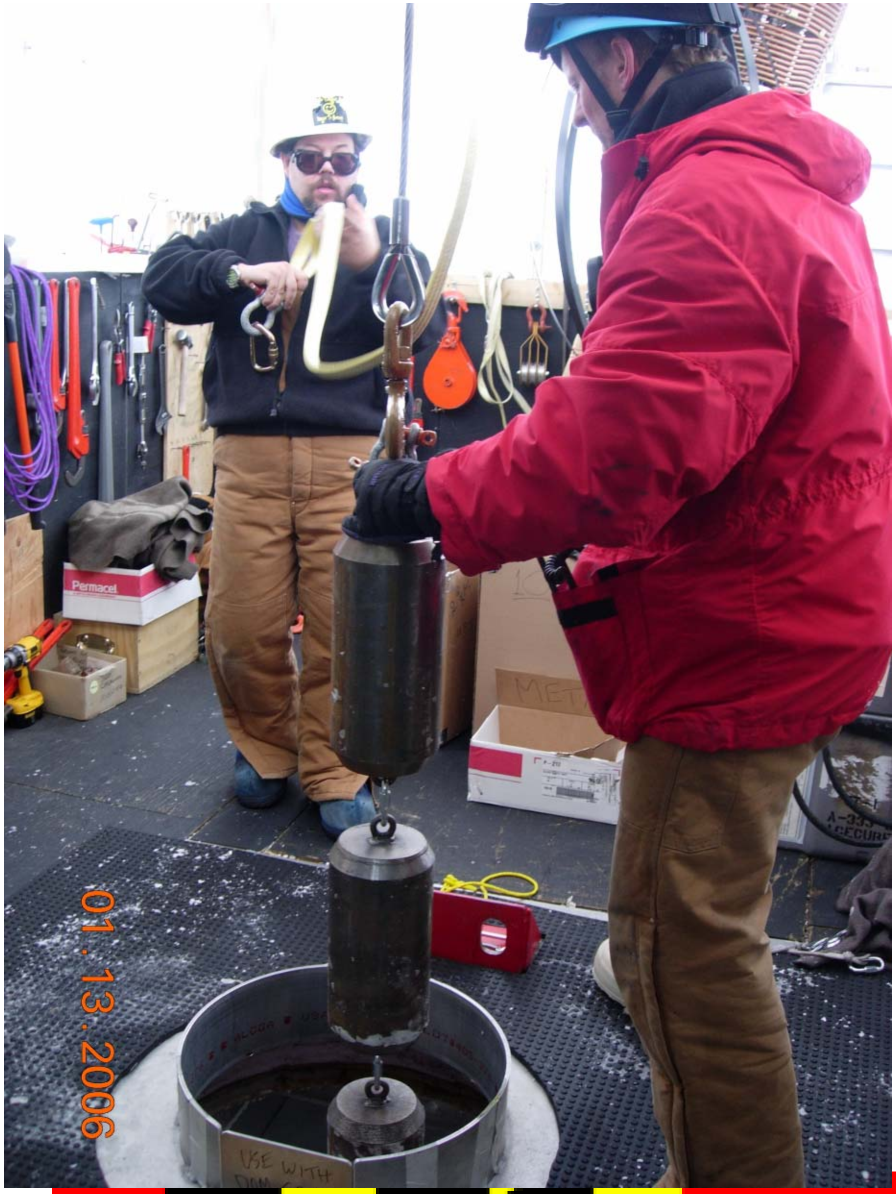





String 49 Drill/Ream/Deployment Profile
Depth(m)
500
0
500
1000
1500
2000
2500
Depth of drill head (m)
Depth of Bottom DOM (m)
DOM installation:
~6min/DOM
Ream
String drop
Drop speed:
18 m/min
Jan 29,2006 6:00 am
Final depth (prel):
2451.0 m
0
10
20
30
40
44.1
50
60
70
Jan 27, 7:05 am
Jan 28, 11:23 am
Time (in hrs)

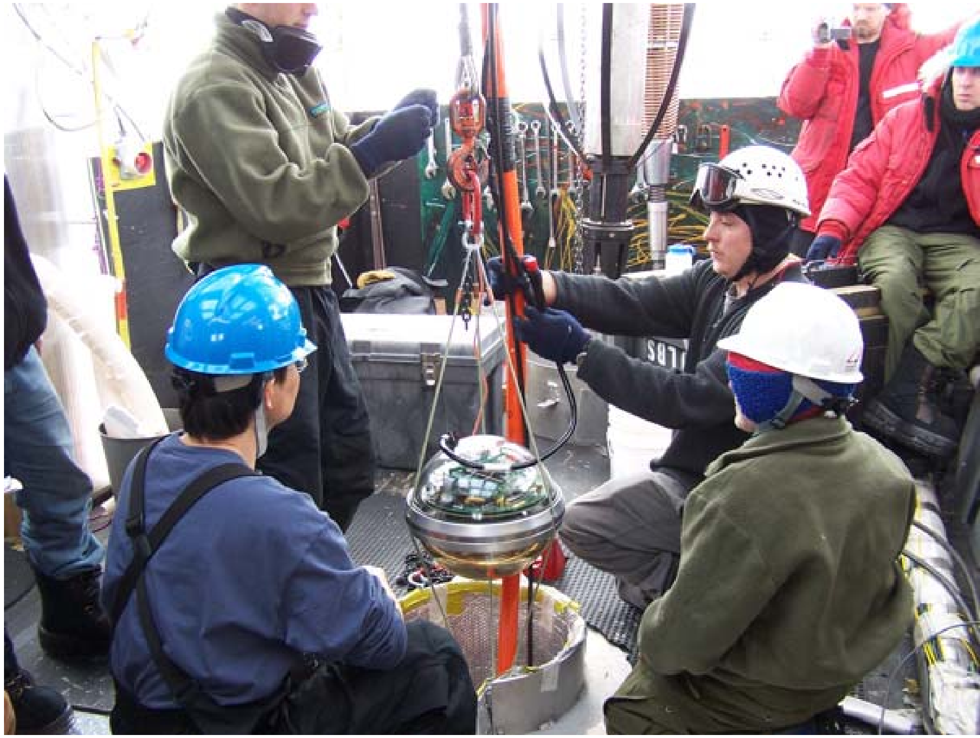
Drilling the Hole

Deployment



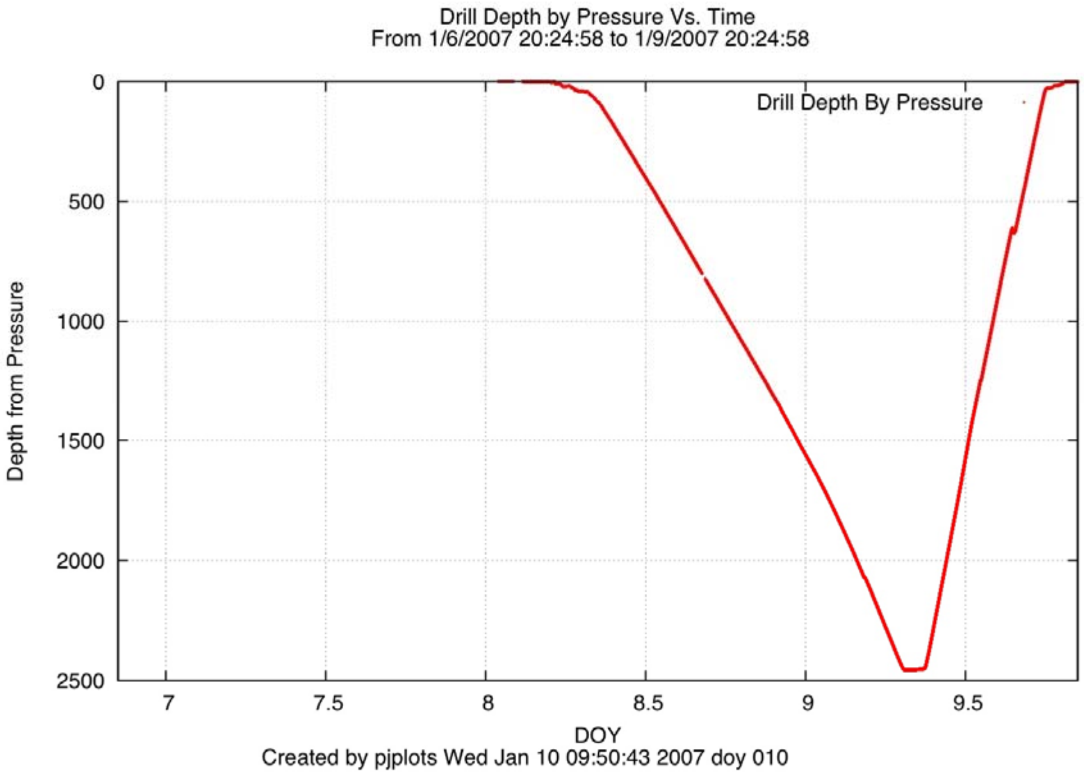
Last Season -

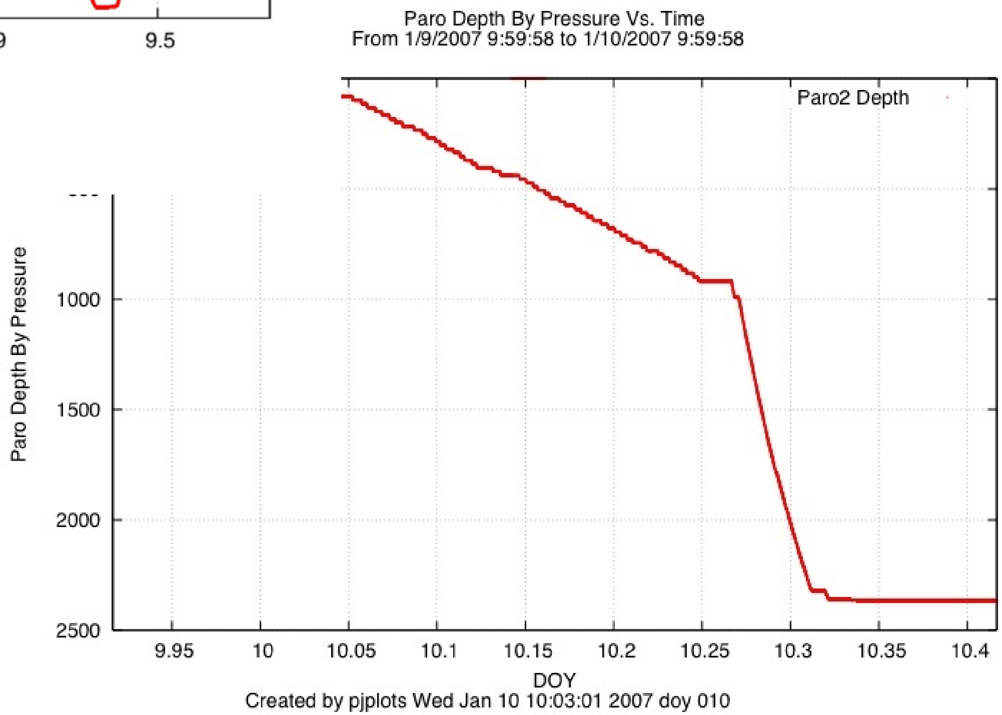
99% of 604 DOMs survived deployment and freeze-in



Lowering the String

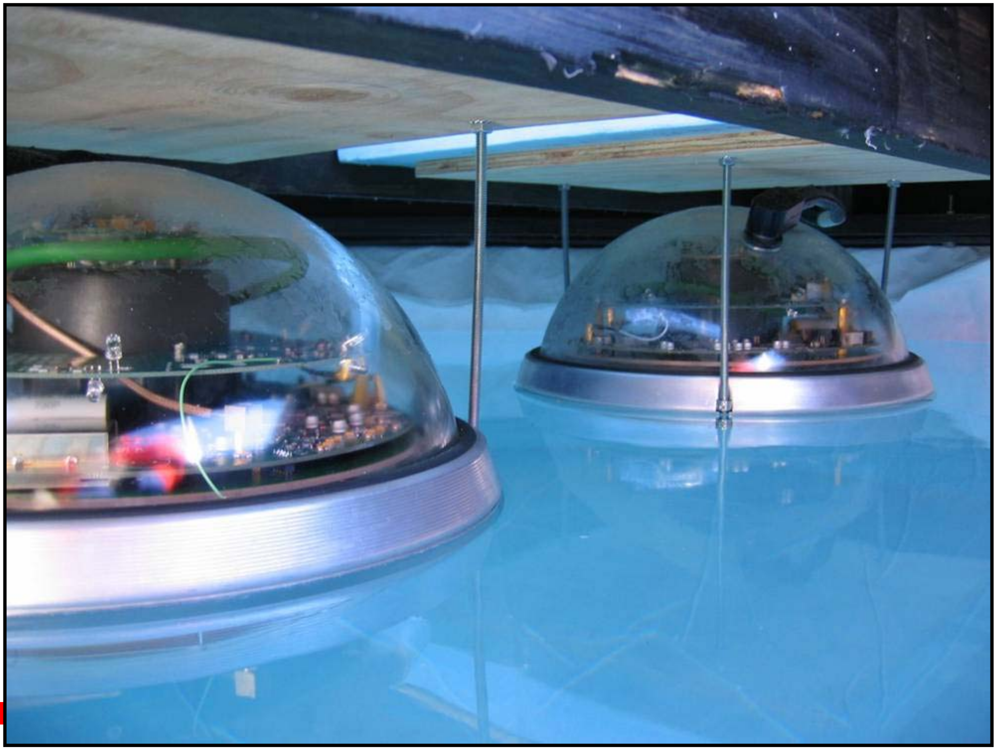
Today at the Pole





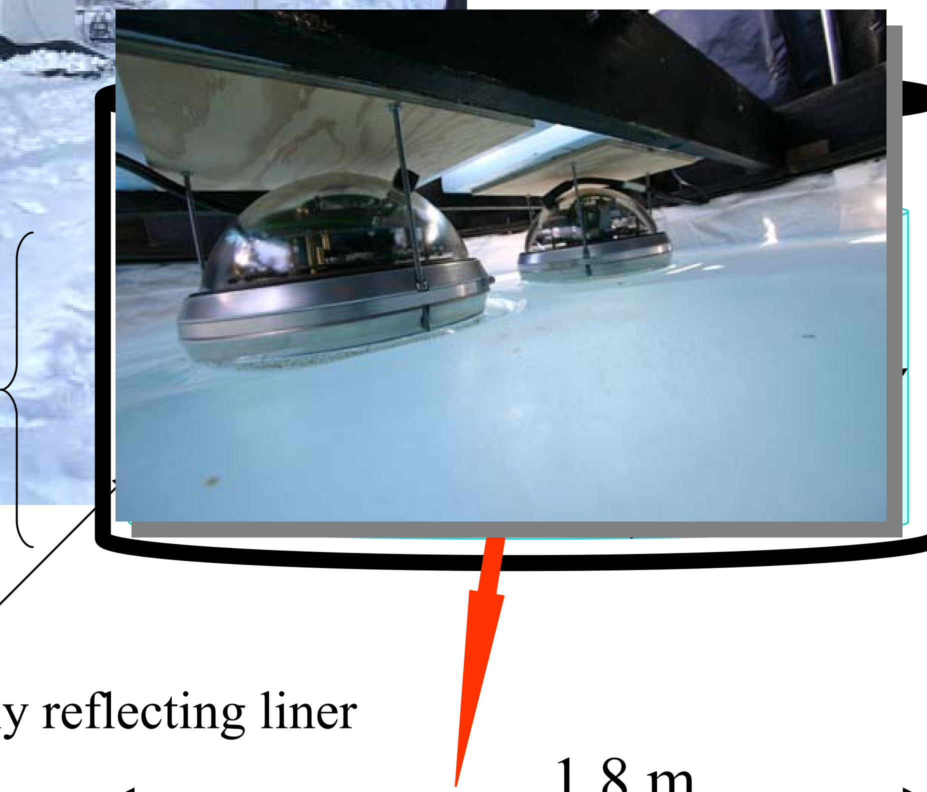
Jan 7, 1500h: Firn drilling commenced
Jan 7, 2200h: firn drilling completed
Jan 8, ~0700h: Ice drilling starts
Jan 9, 1800h ream was completed
Jan 9, 21:45h deployment start
Jan 9, 23:25h first breakout attached
Jan 9, 06:30h drop starts
Jan 9, 08:05h tie-off
Total drill time: ~37 hours
Total deployment time: ~10 hours.

IceTop – the Surface Airshower Detector



Each 2 m dia. IceTop tank contains two Digital Optical Modules. The freezing of the water is done in a controlled manner to produce clear ice.

IceTop tank assembly

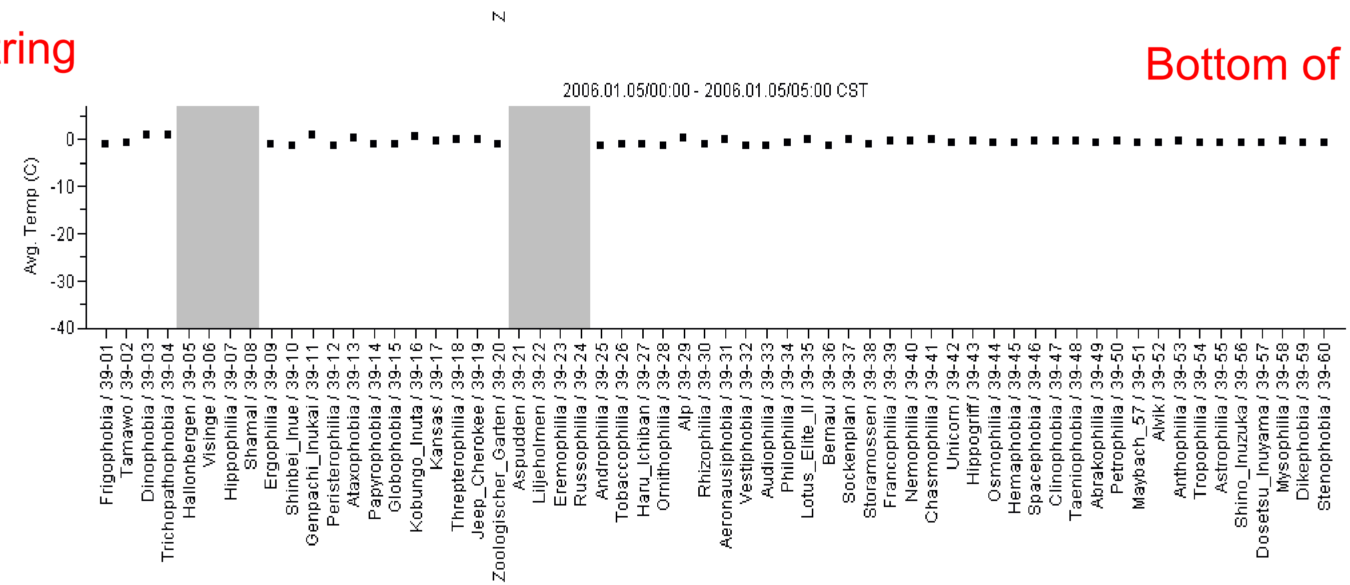


New IceCube Counting House

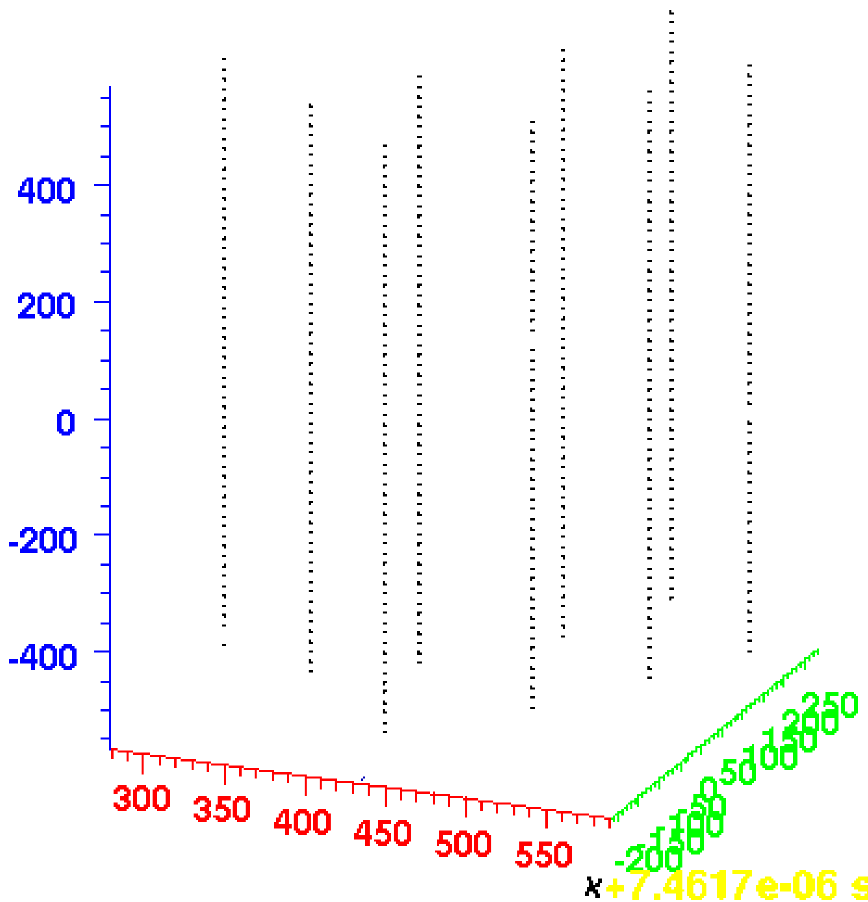
String 39 two-week freeze-in movie

Top of String

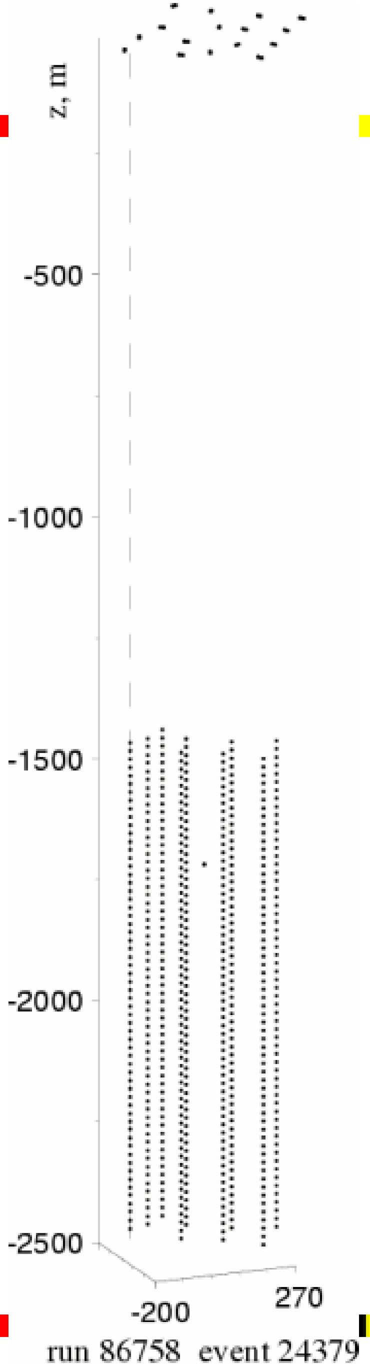
Bottom of String

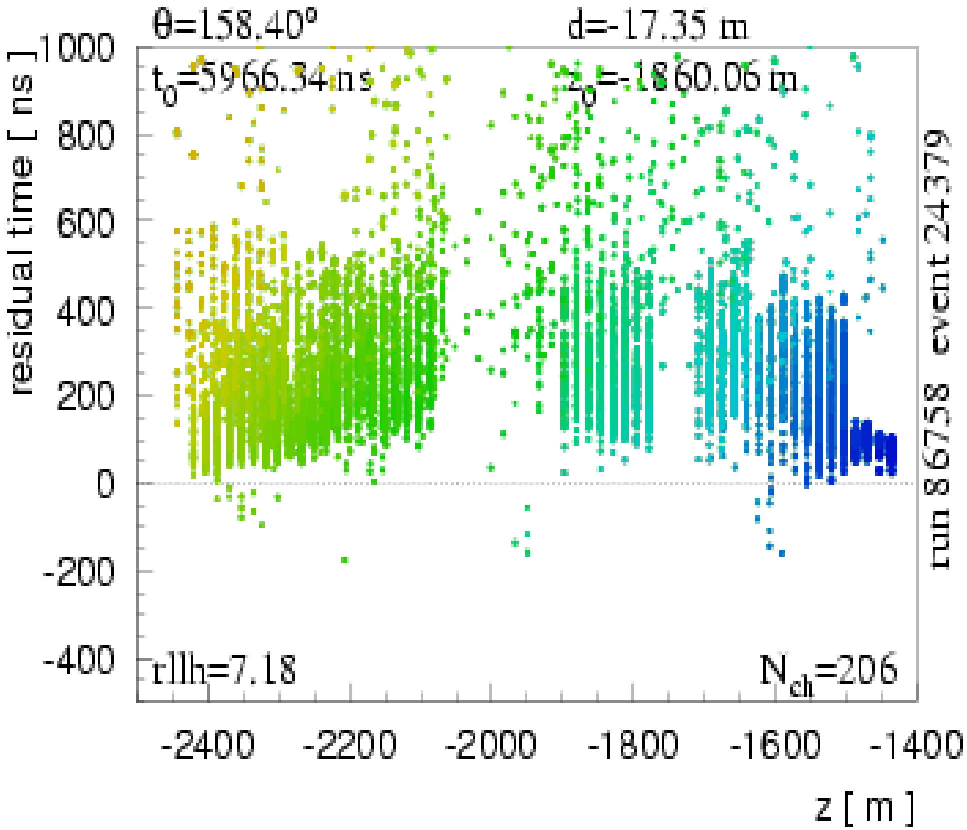


Up-Going Neutrino Event

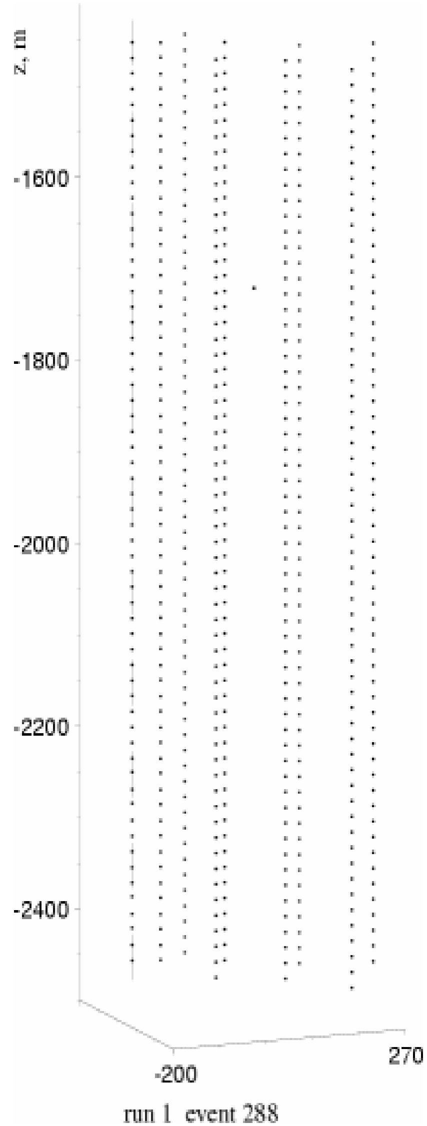


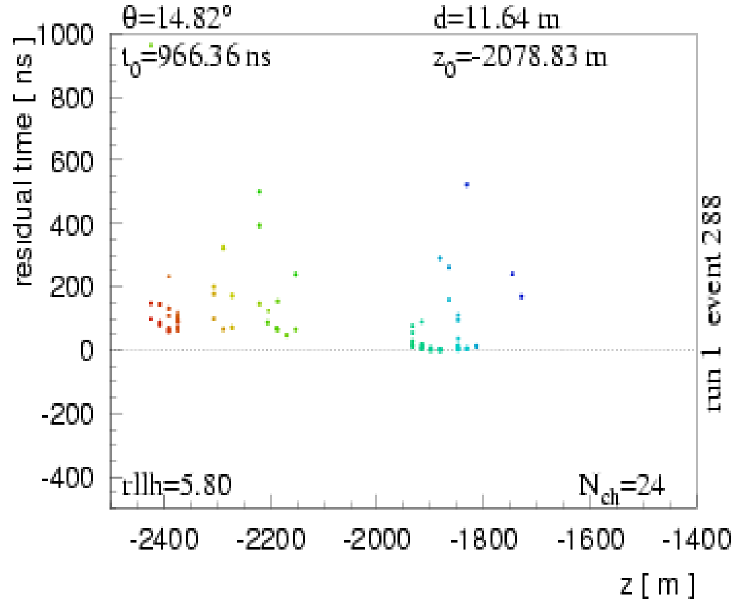
Coincident airshower (IceTop) and muon (IceCube)



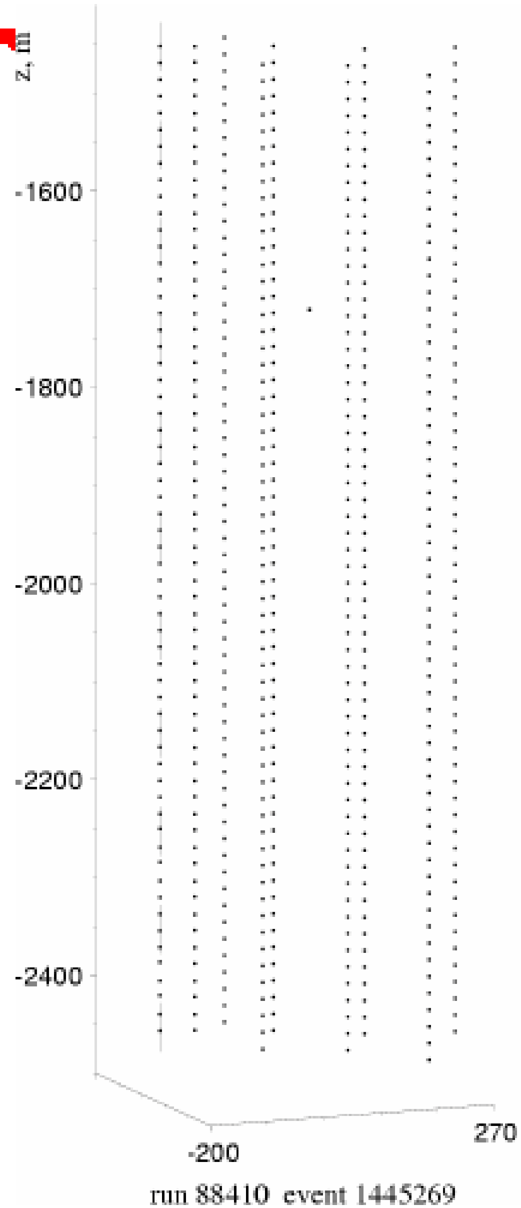


Neutrino-induced muon candidate in the 9-string array

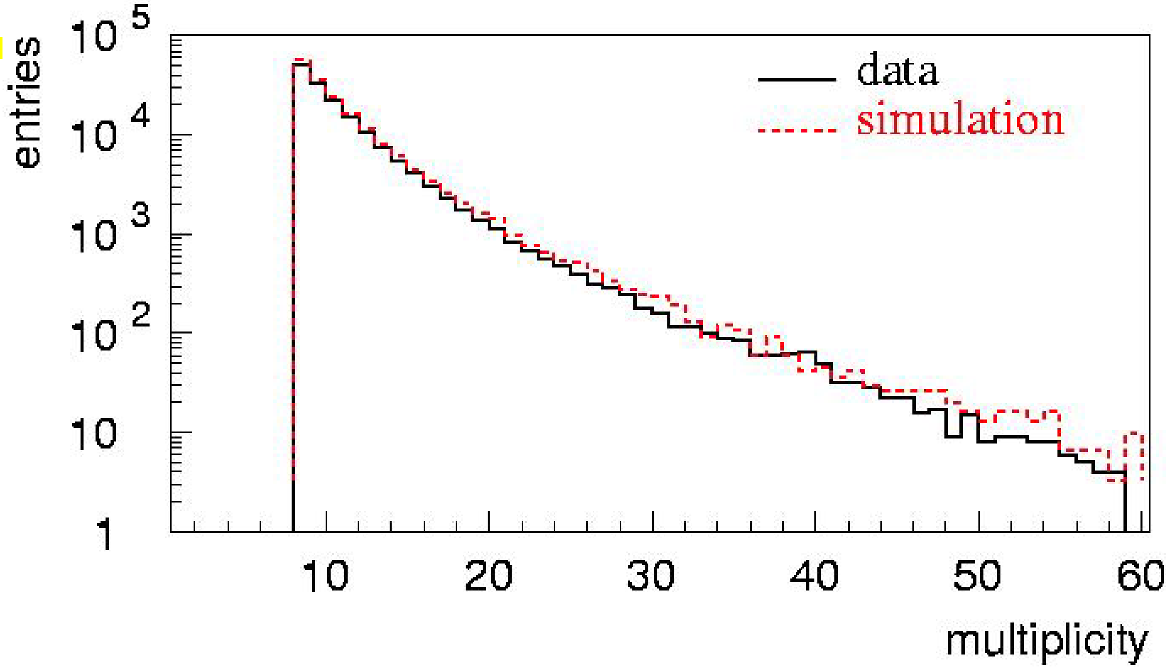


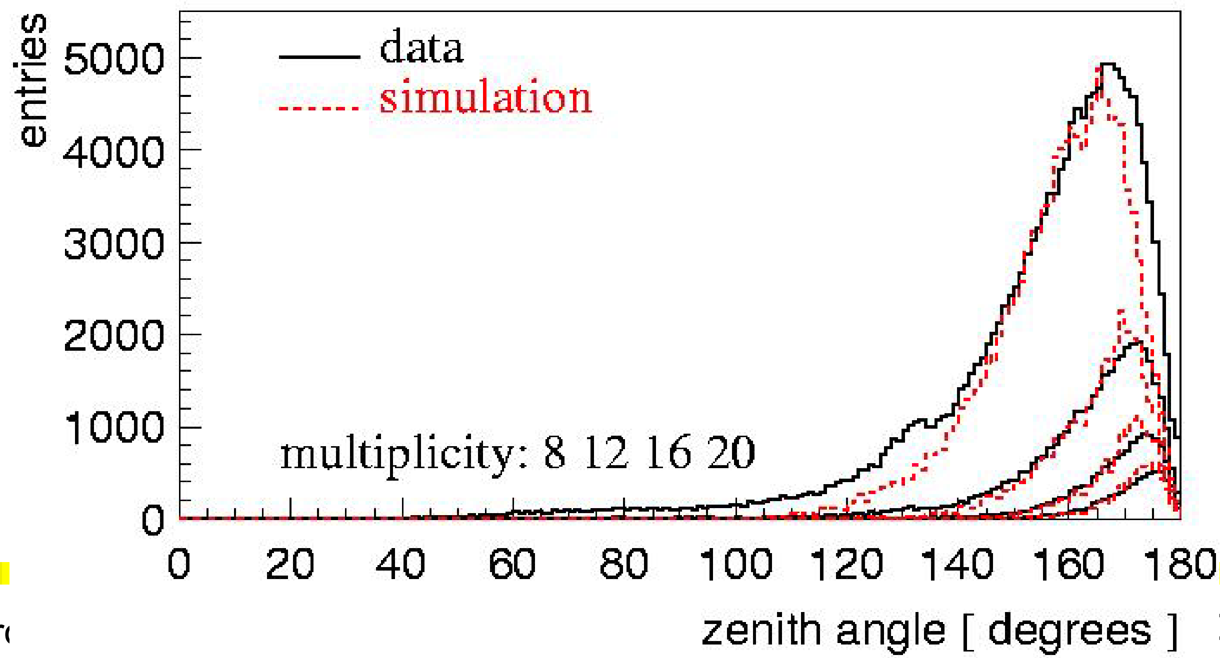


An upgoing muon involving 7 of 9 strings



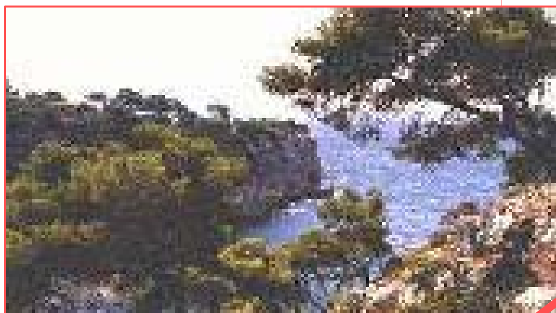
IceCube muon data reconstruction



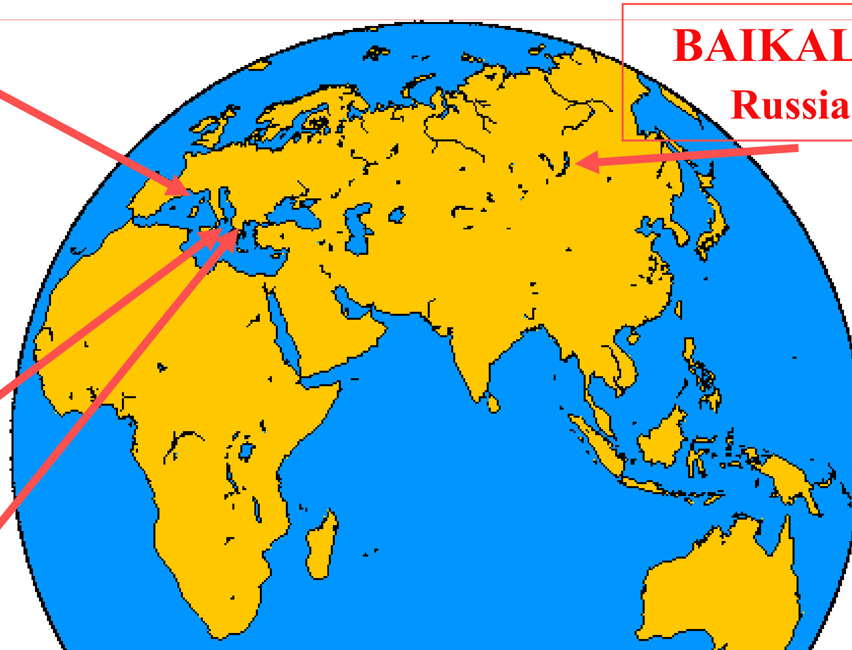


Large Scale Neutrino Detectors

ANTARES
La-Seyne-sur-Mer, France



BAIKAL
Russia

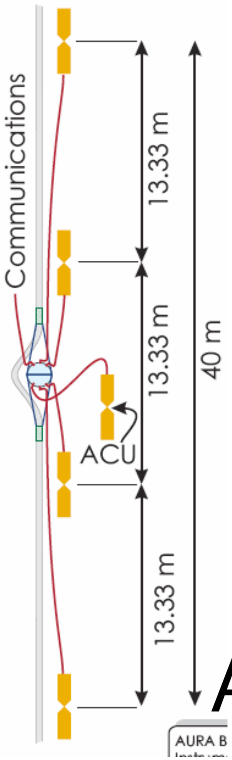


NEMO
Catania, Italy

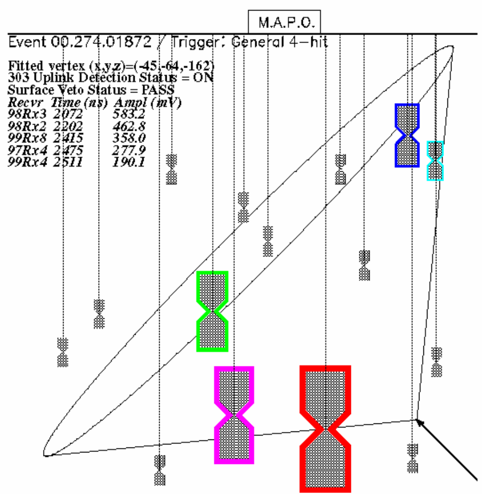
NESTOR
Pylos, Greece

IceCube, South Pole, Antarctica

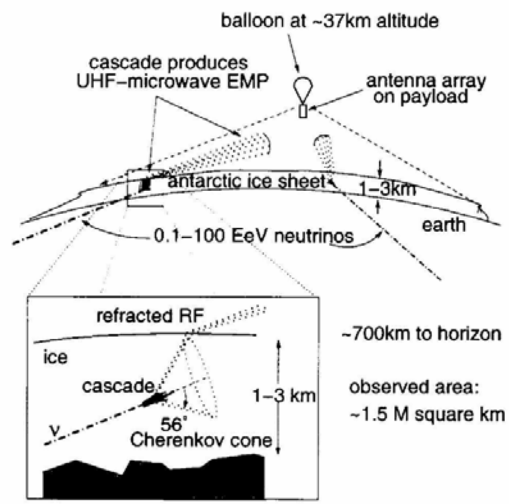
Radio Cherenkov Detectors



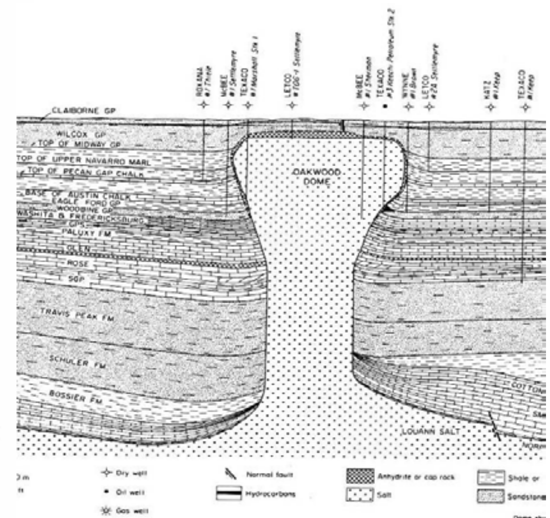
AURA



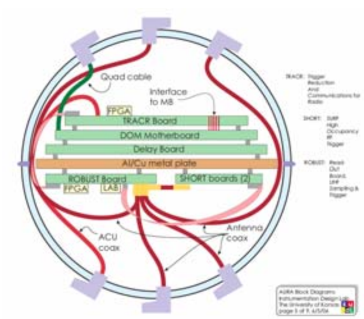
Rice



Anita



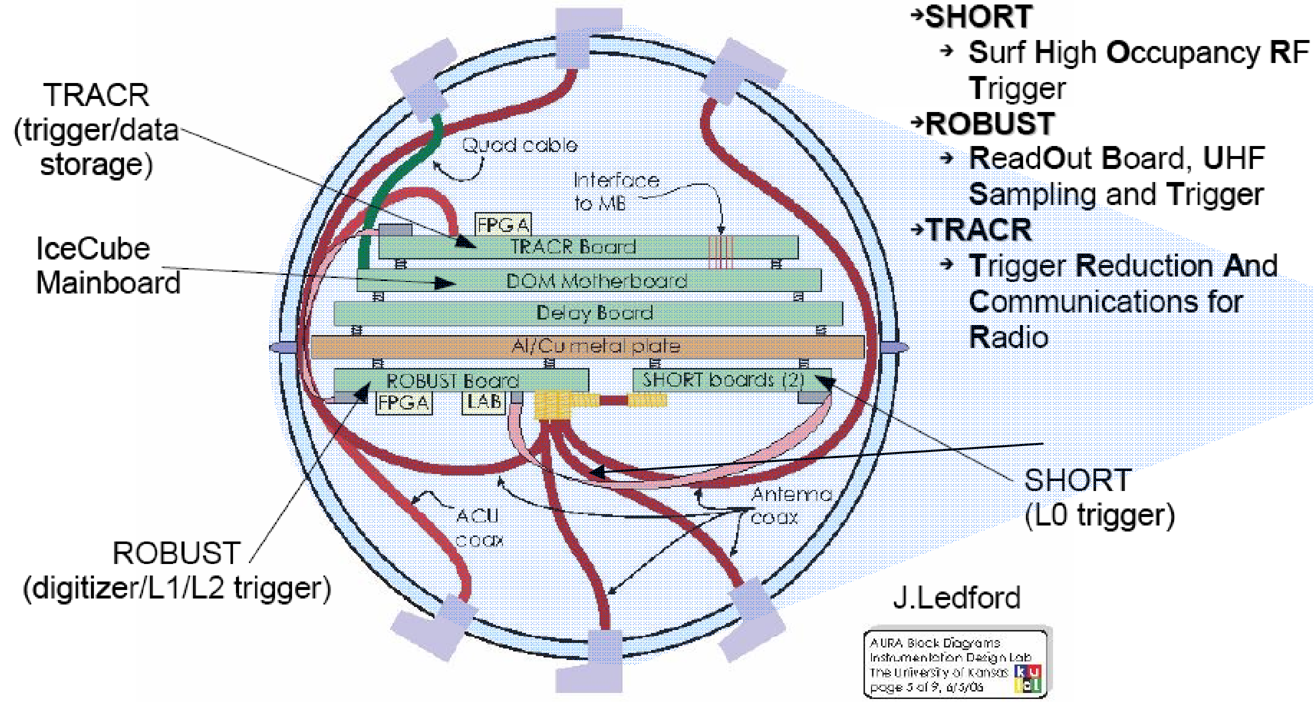
Salsa

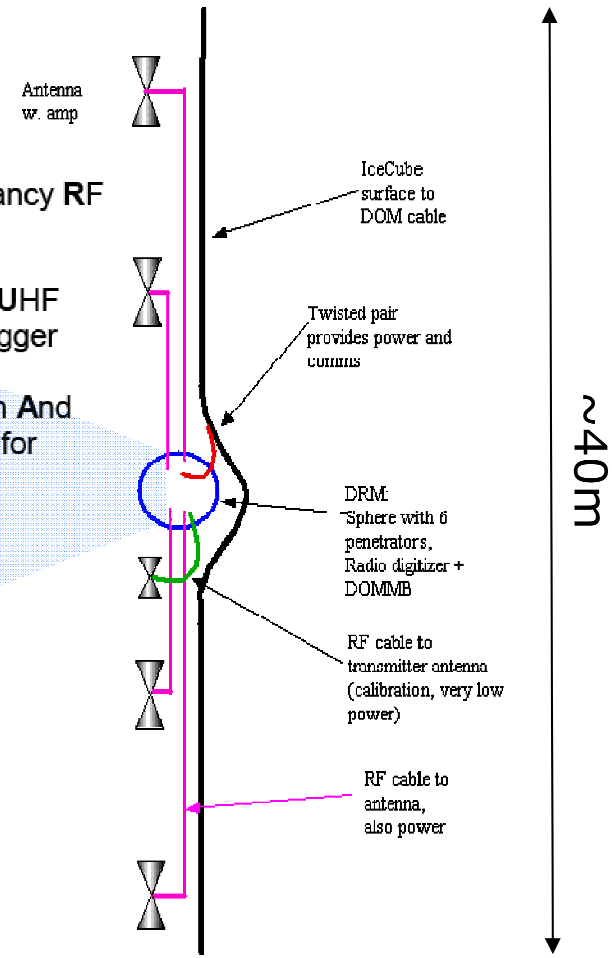


Radio – good signal for GZK energies

AURA (Askaryan Underice Radio Array)

Digital Radio Module (DRM):



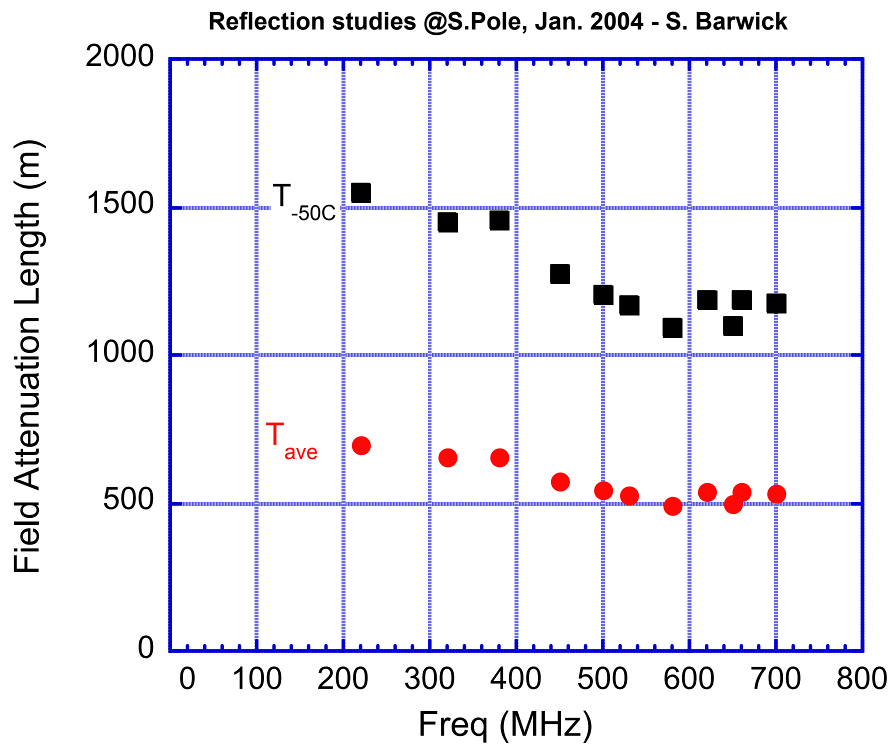


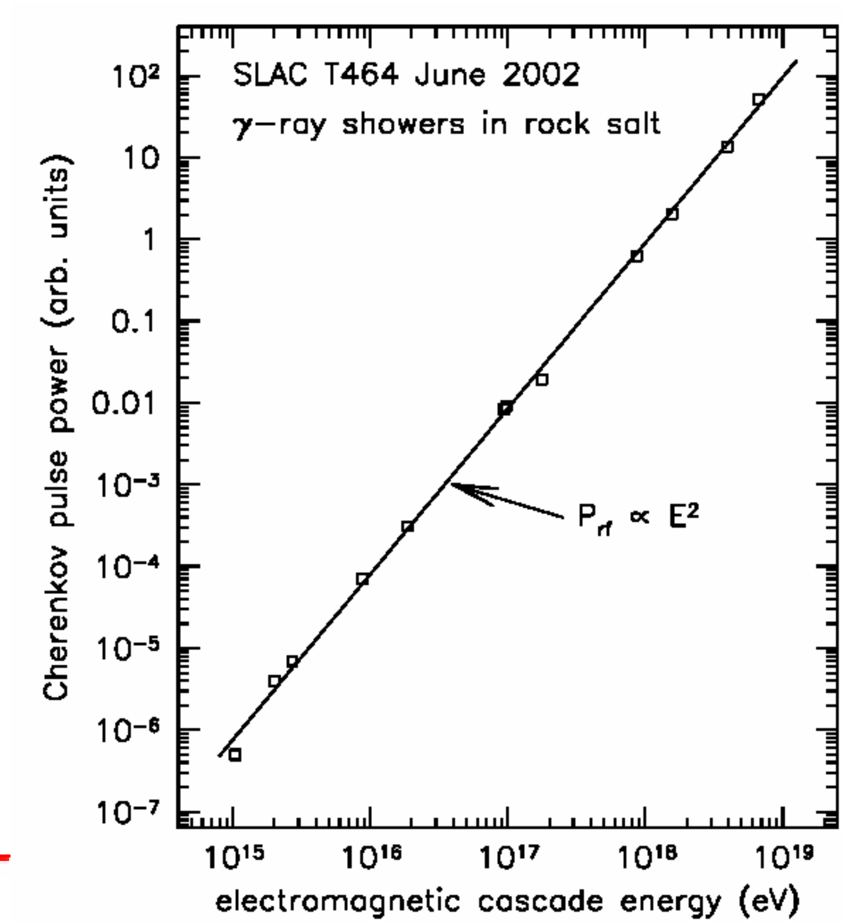
Four clusters (4 antennas each) to be deployed next season

Radio – a path to a giant array

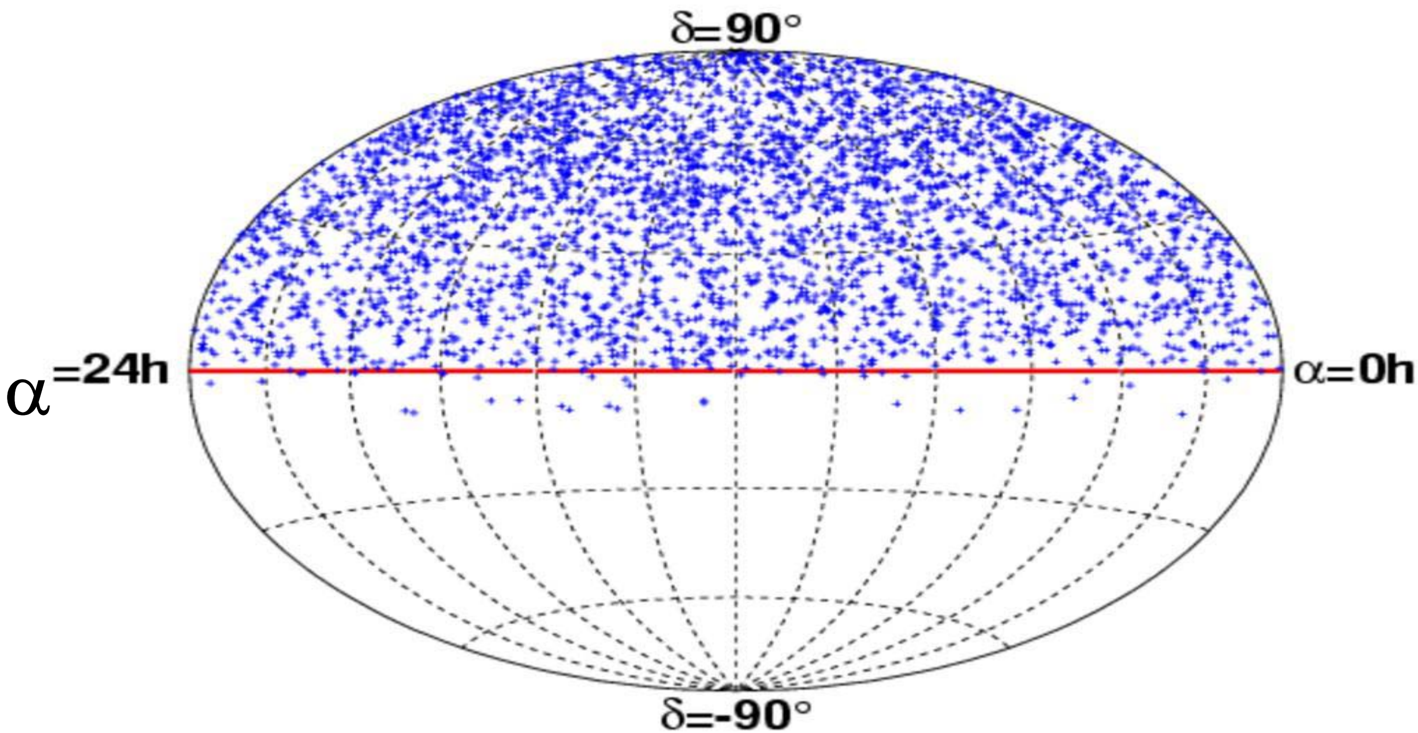
Cold ice is very transparent to radio- a sparse large area array is possible

Power of the rf signal grows with the square of the energy- healthy signals for GZK energies



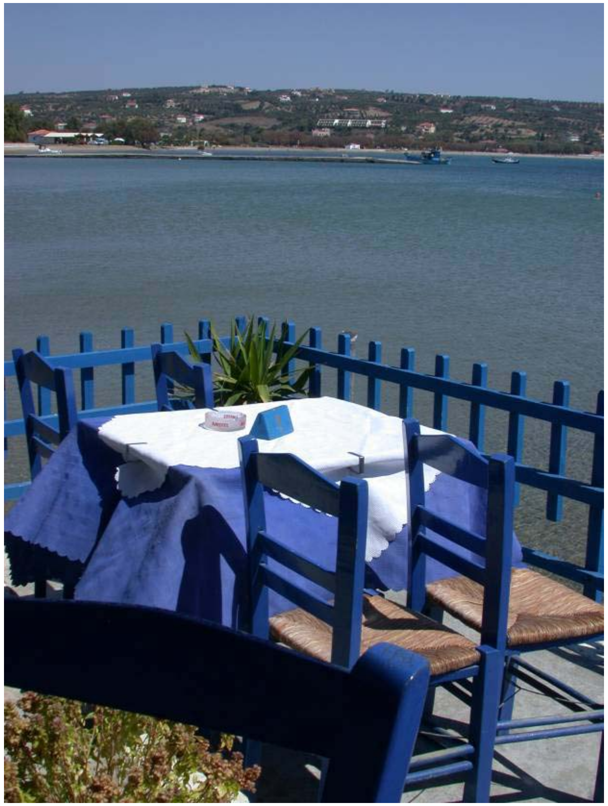


The Era of Neutrino Astronomy has Begun!



Working on a KM^3 Experiment

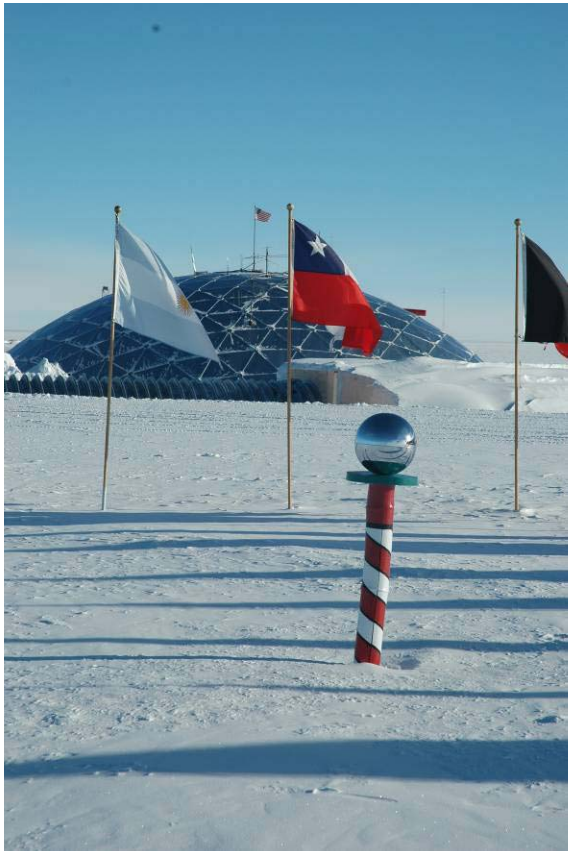
The Choices:

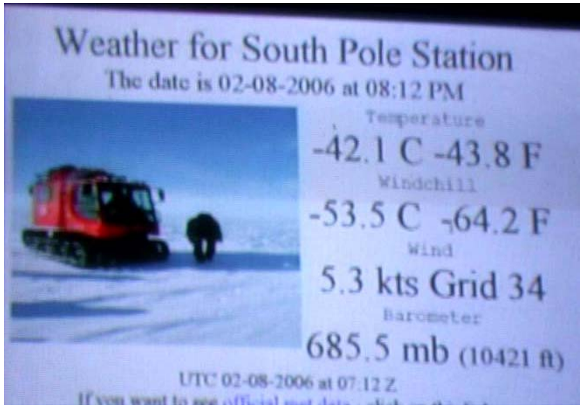


Nestor

Working on a KM^3 Experiment

The Choices:





IceCube