Simulation of a hybrid optical-radio-acoustic neutrino detector at South Pole

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Outline

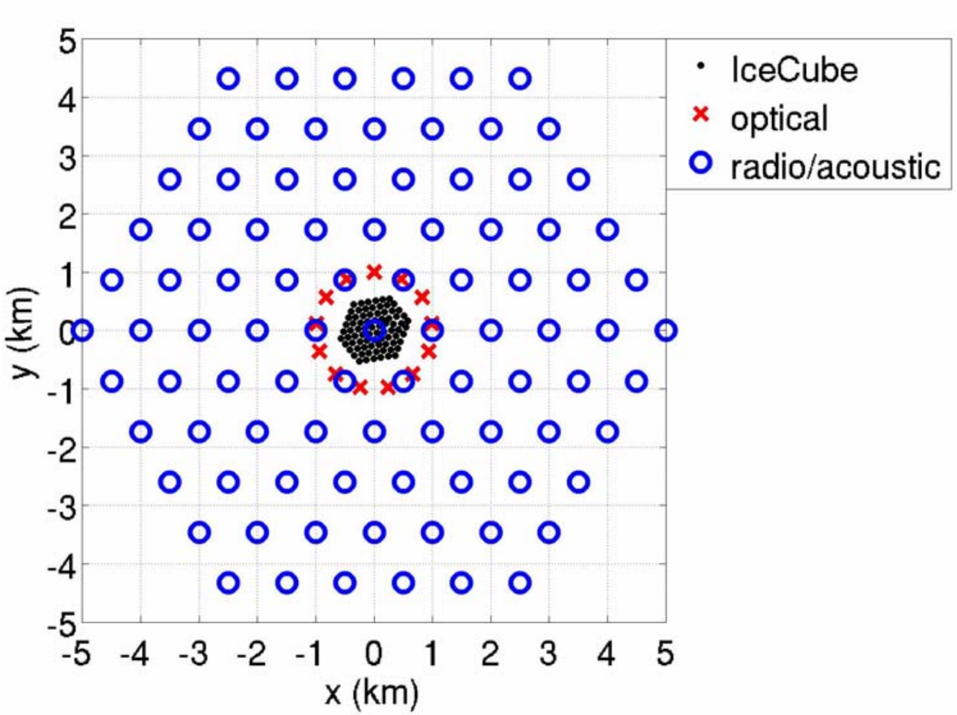
- Why a hybrid detector?
- The big picture:
  simulation of a 100 km^3 hybrid detector (2005)
- Past/present experiments:
  AMANDA/IceCube, RICE, SPATS
- A possible intermediate step:
  a high energy optimization for the IceCube outer strings
- Results & prospects

Why a hybrid detector?

- UHE physics requires large volumes due to the low flux
- To instrument these volumes with optical detectors impossible
- Optical sensors + ice properties best at 10 TeV – 10 PeV; calibration in this range possible with atmospheric muons and neutrinos
- Radio and acoustic detectors have high energy thresholds (~100 PeV), no real calibration source is available
- Hybrid events detected by more then one technique would:
  - allow calibration of radio and acoustic with the optical method
  - make possible cross-calibration between radio and acoustic
  - improve energy and direction reconstruction
  - enhance background rejection

A large scale detector design

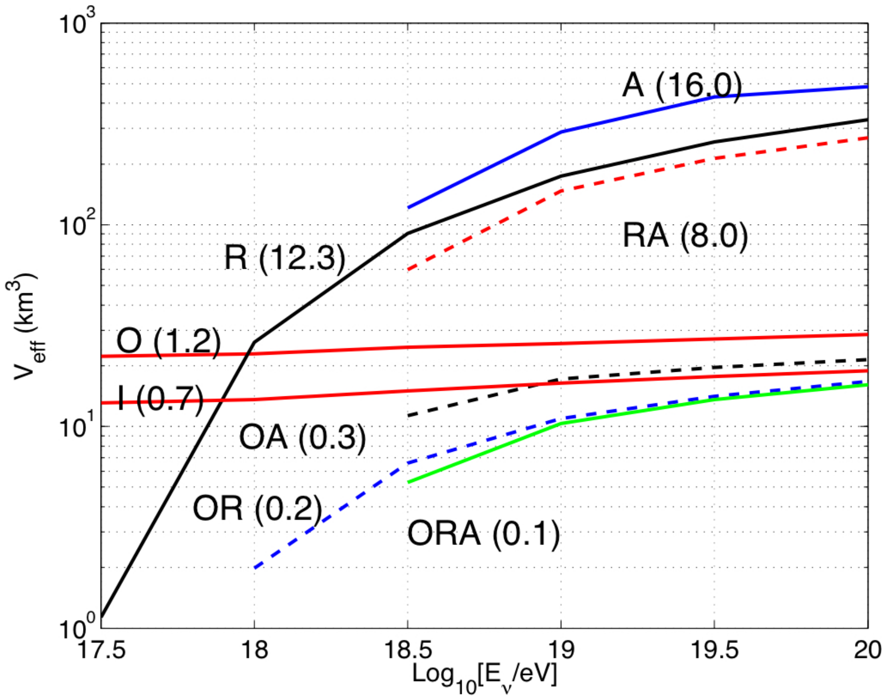
- Optical-Radio-Acoustic detector surrounding IceCube
  instrumented volume: ~(110 +3)km^3
  [D. Besson et al., astro-ph/0512604]



- Optical devices:
  80 IceCube + 13 IceCube-Plus strings
  at a 1 km radius, each with:
  60 DOMs, spaced every 17 m
  from 1.45 km to 2.45 km depth

- Radio/Acoustic devices:
  91 holes, 1 km spacing, each with:
  5 radio receivers spaced every 100 m from 200 m to 600 m depth
  300 acoustic receivers spaced every 5 m from 5 m to 1500 m depth

Effective volumes & event rates



- I: IceCube
  O: Optical
  R: Radio
  A: Acoustic
- ESS GZK flux model ($\Omega_\Lambda = 0.7$)
  [R. Engel, D. Seckel and T. Stanev
  Phys. Rev. D 64, 093010 (2001)]

Detection option	GZK events/year*)
IceCube	0.7
Optical	1.2
Radio	12.3
Acoustic	16.0
Optical+Radio	0.2
Optical+Acoustic	0.3
Radio+Acoustic	8.0 !!!
Opt.+Rad.+Acou.	0.1
TOTAL	21.1

Present experiences

- AMANDA/IceCube (1997 – present):
  demonstration of excellent optical detection in ice
  many physics results available
  [e.g. J. Kyriluk et al. astro-ph/0806.1717]

- RICE (1999 - present):
  test bed for radio detection and background identification
  best radio flux limits in the range 100 PeV -100 EeV until 2008
  [e.g. D. Besson, J. Phys. Conf.Ser.81:012008,2007]

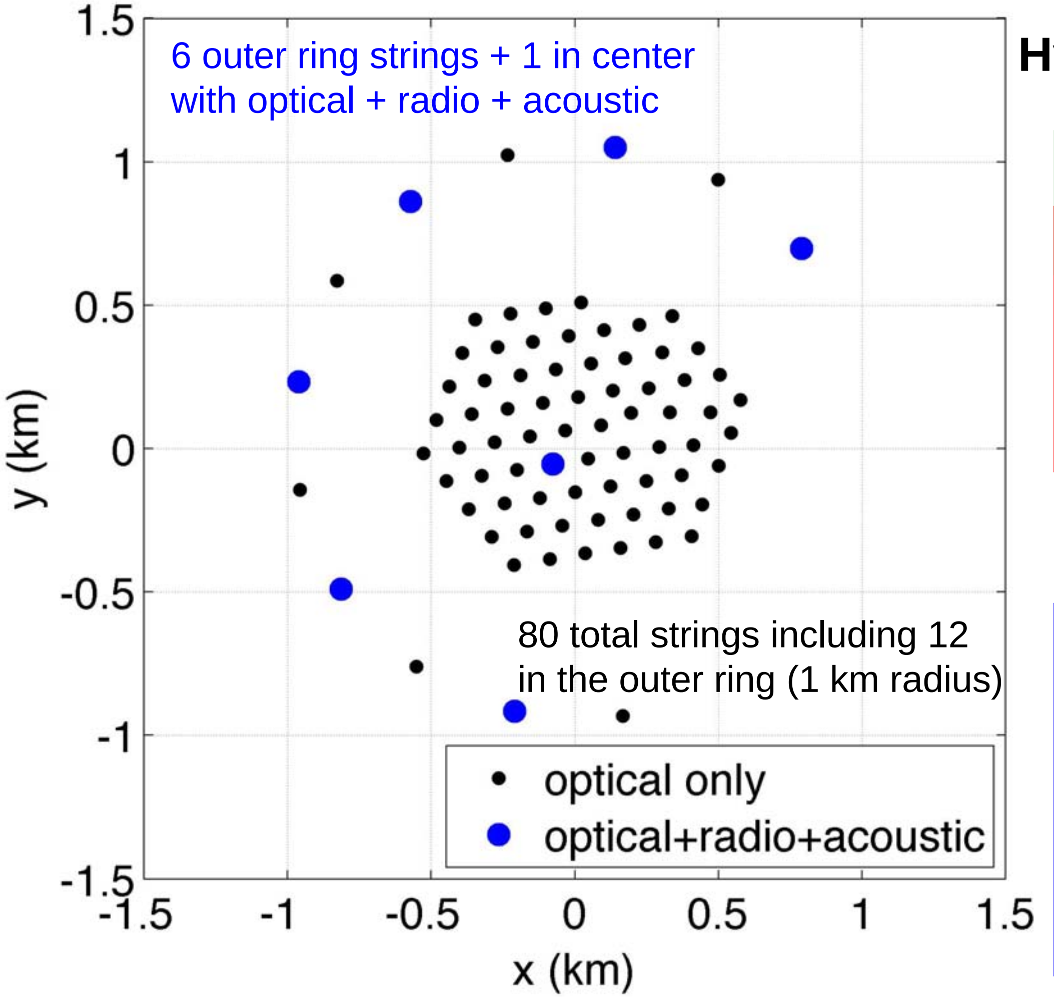
- SPATS (2007 - present):
  in-situ measurement of acoustic properties
  (speed of sound and noise profiles, attenuation length)
  [e.g. S. Böser et al. astro-ph/0708.2089v1]

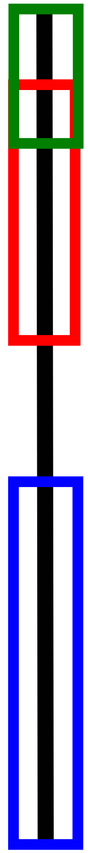
An intermediate step

- High energy outer ring could optimize IceCube sensitivity at ≥ PeV
- Intermediate between current efforts and possible large-scale hybrid GZK observatory
- Goal: apply the same strategy as presented in astro-ph/0512604
- Determine V_{eff} of Optical, Radio, and Acoustic methods: each, total, and overlap

Simulated array geometry: HORUS

Hybrid **O**ptical **R**adio **U**ltrasound **S**etup





5 radio antennas
1 every 100 m from 200 to 600 m

60 acoustic sensors
1 every 15 m from 215 to 1100 m

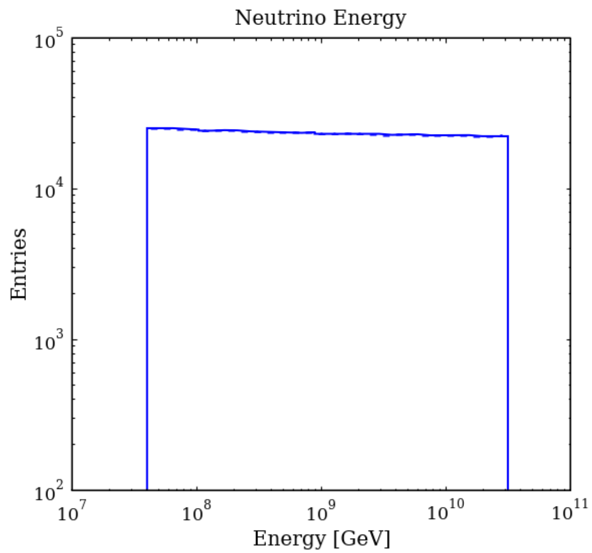
normal optical string with 60 DOMs
1 every 17 m from 1.45 km to 2.45 km

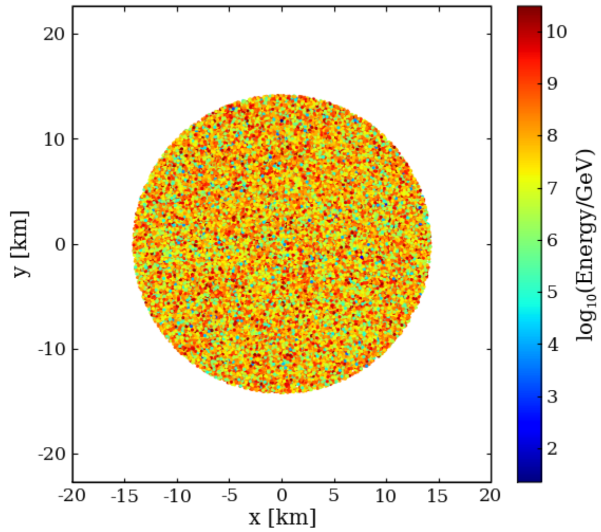
Simulated neutrino events

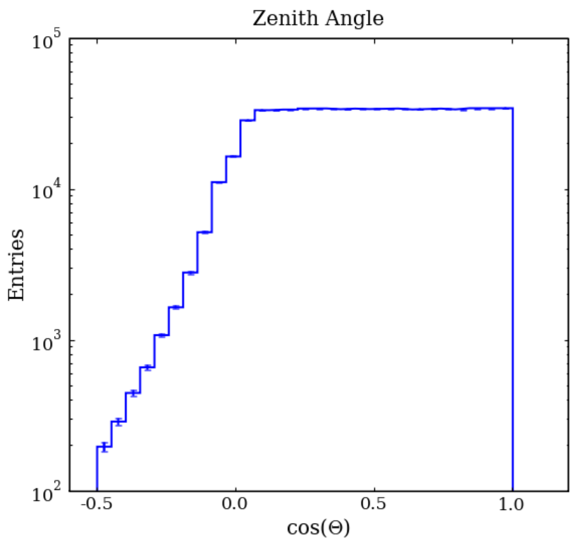
- Generation cylinder: 10 km radius, 20 km length
- E^{-1} from $10^{16.5}$ eV to $10^{19.5}$ eV
- 2 flavors simulated: $\nu_e + \overline{\nu_e}, \nu_\mu + \overline{\nu_\mu}$

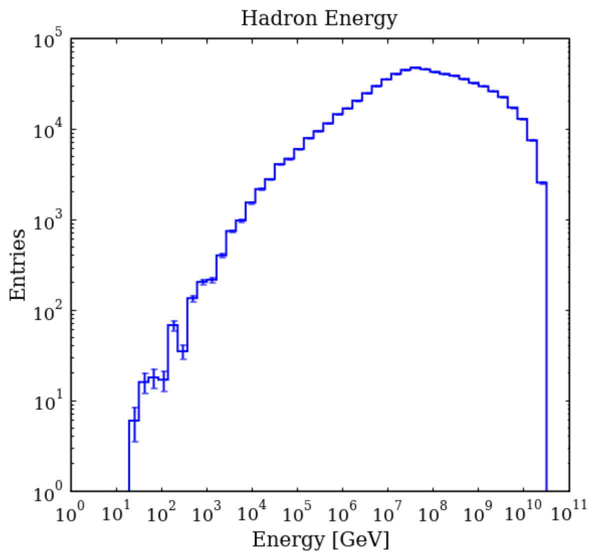
  problems with the generator for $\nu_\tau + \overline{\nu_\tau}$
- Angular distribution around zenith, from 0° to 120°
- 10^6 events for each flavor

Neutrino events before detection









Optical simulation

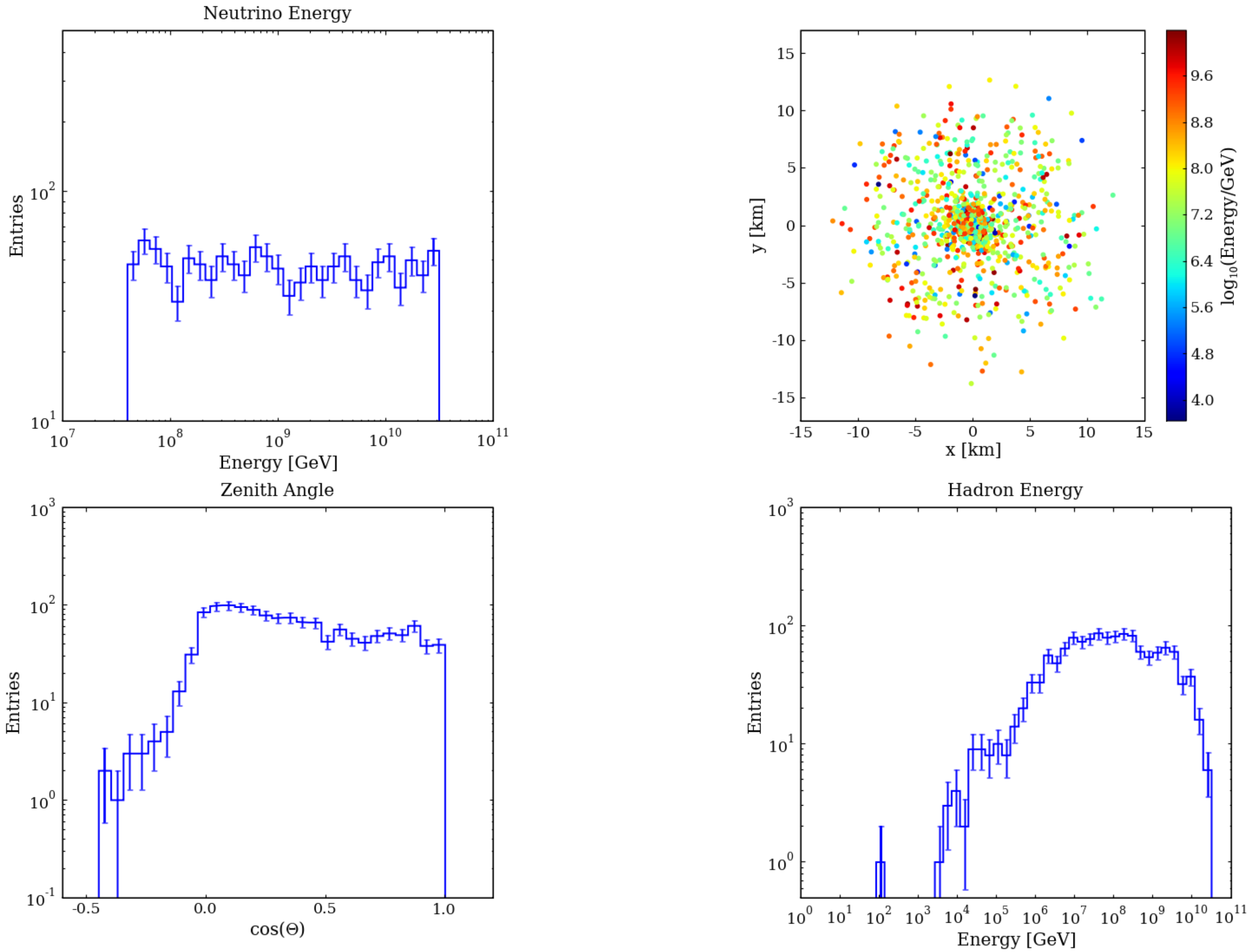
- IceCube 80 strings including 12 in the outer ring
- Particle propagation for muons and electrons
- LPM effect taken into account
- Light propagation using the ice model with dust layers
- DOMs simulated as they are in IceCube

  [A. Achterberg et al., astro-ph/0604450]
- Trigger conditions:

  - global coincidence: 8 modules in 5 μs

  - local coincidence: 2 nearby modules in one string hit in 1 μs

Neutrino events detected by optical



Radio simulation

- Radio signal from shower modeled as in:

  [J. Alvares-Mũniz, R.A.Vásquez and E. Zas, astroph/0003315 (2000)]

- LPM effect modeled as in:

  [J. Alvares-Mũniz and E. Zas, astroph/9706064 (1997)]

- Assume max field attenuation length of 1.2 km

- Assume antenna with:

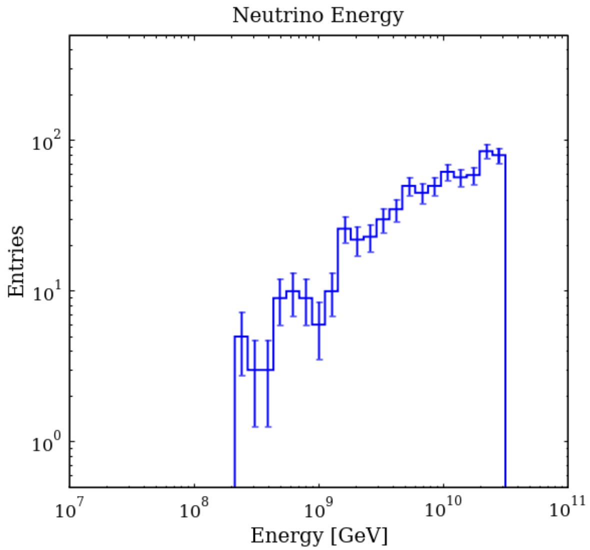
  - peak effective height = 0.27 m @ 200 MHz

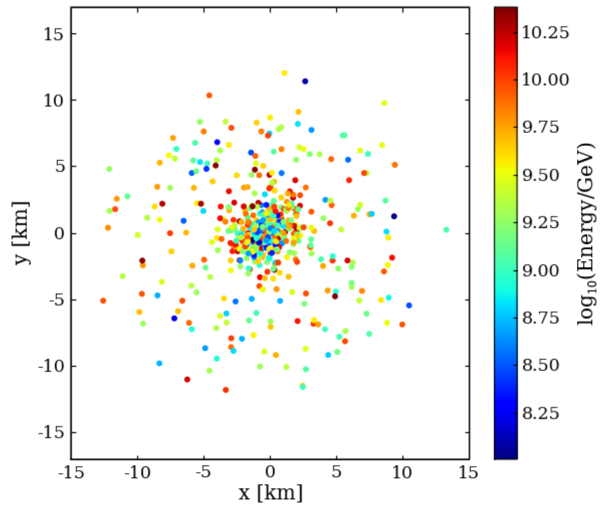
  - Gaussian bandwidth, sigma ~ 60 MHz

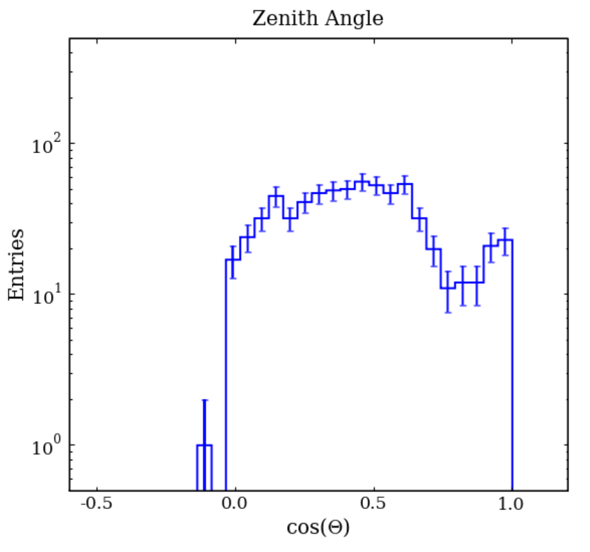
  - sharp high pass filter at 110 MHz

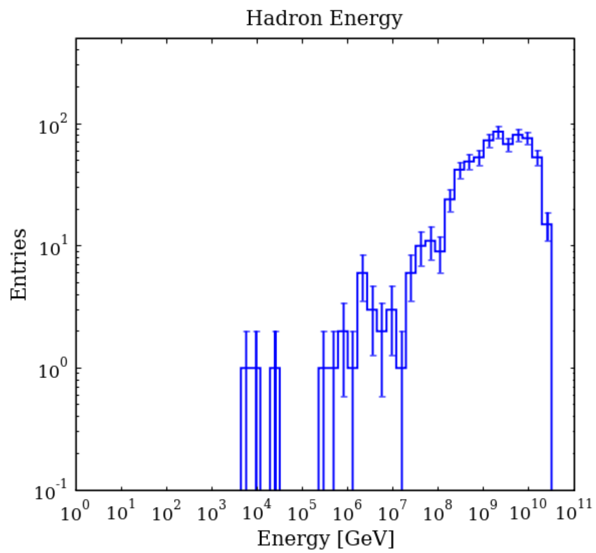
- Trigger: ≥ 4 antennas above 4 sigma

Neutrino events detected by radio





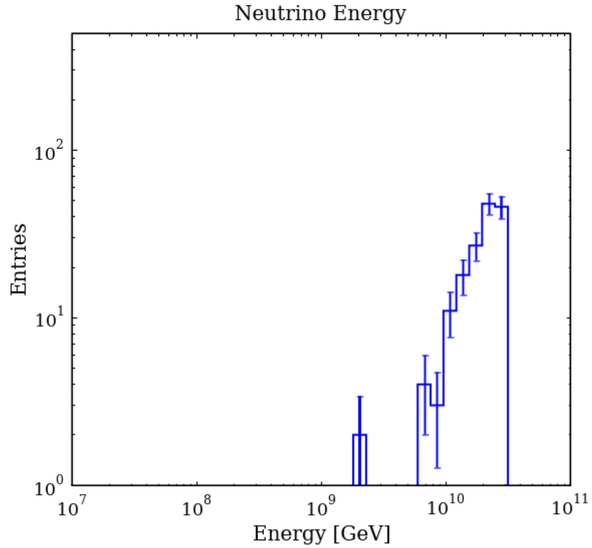


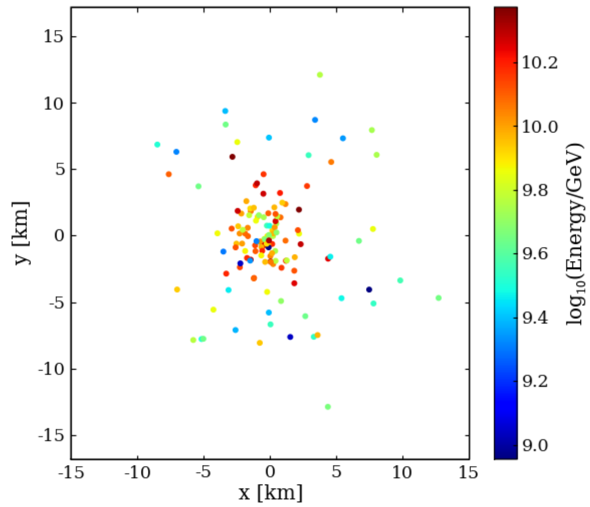


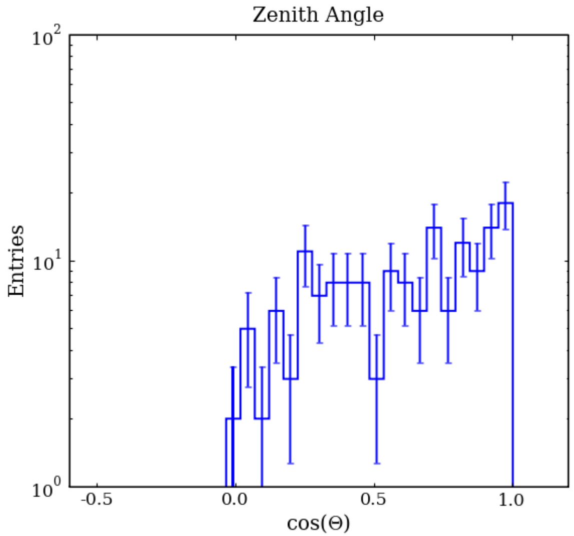
Acoustic simulation

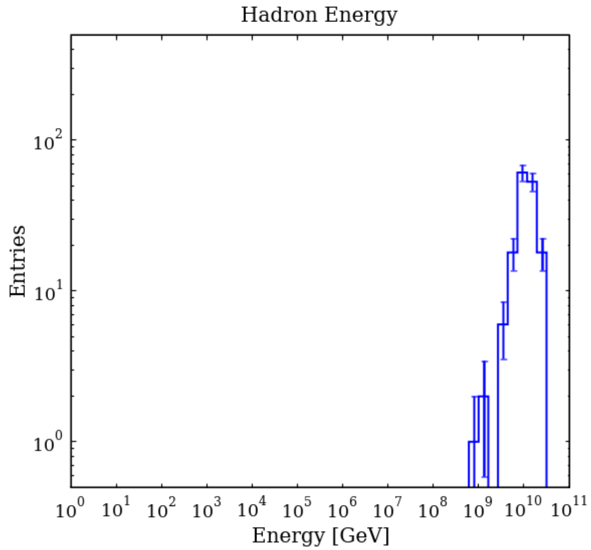
- Ignore electromagnetic showers from charged current electrons (signal negligible due to LPM)
- Modified NKG (Nishimura-Kamata-Greisen) parameterization for hadronic showers (lengthened by LPM)
  [http://icecube.berkeley.edu/~justin/showers.pdf]
  [J. Alvares-Mũniz and E. Zas, Phys. Lett. B 434, 396 (1998)]
- Ice properties and attenuation from P. B. Price's model
  [P. B. Price, J. Geophys. Res. 111, B02201 (2006)]
- Integrate over depth-dependent attenuation model
- Signal simulation similar to that used for SAUND
  [J. Vandenbroucke, G. Gratta and N. Lehtinen, ApJ. 621, 301 (2005)]
- Assume uniform frequency and angular sensor response
- Trigger: ≥ 3 sensors above 9 mPa

Neutrino events detected by acoustic

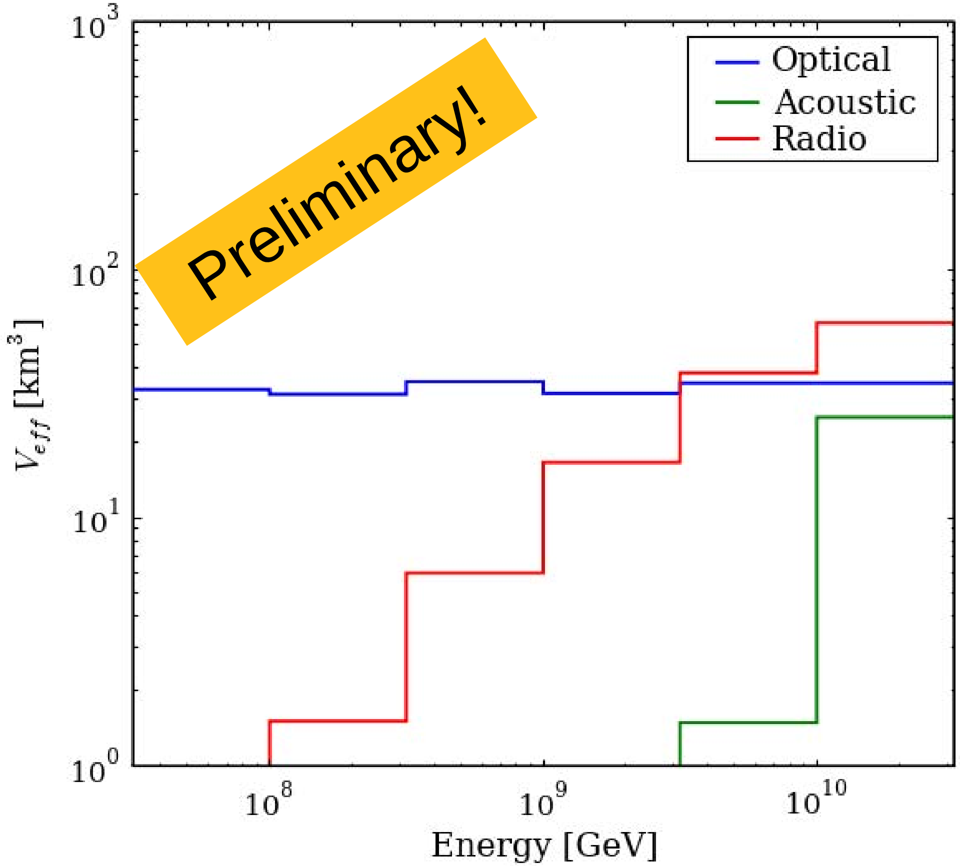








Effective volumes



- Effective volume does not include ν_τ events
- Expected increase:
  - 1.2 for the optical channel
  - 1.3 for the radio and the acoustic channels

Event rates

- Event rates assuming the ESS GZK flux model ($\Omega_\Lambda = 0.7$)
  [R. Engel, D. Seckel and T. Stanev Phys. Rev. D 64, 093010 (2001)]
- ν_τ contribution not included
- IceCube results higher than in the previous simulation, but:
  - Geometry of the ring is different
  - New software
  - One additional channel: $\nu_e + \nu_\mu$ (+ showers) vs ν_μ only
  - Trigger level is weaker: 8 hits in 5 μs vs 5 in 2.5 μs

Detection option	GZK events/year*)
IceCube	2.39
Optical	3.99
Radio	1.68
Acoustic	0.43
Optical+Radio	0.098
Optical+Acoustic	0.043
Radio+Acoustic	0.089
Opt.+Rad.+Acou.	0.012
TOTAL	5.568

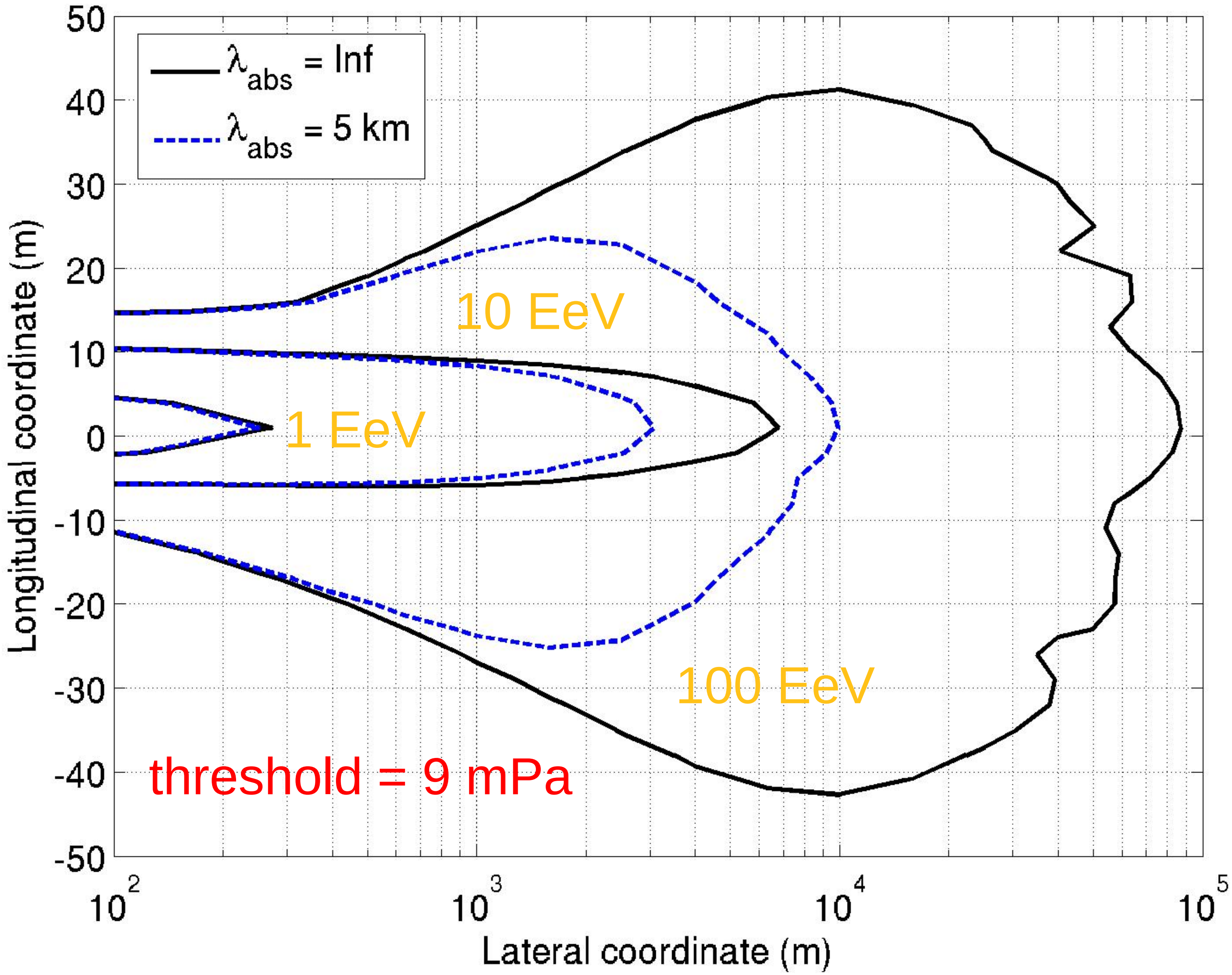
Preliminary!

Results & Prospects

- Outer ring gives IceCube the chance of detecting twice as many GZK neutrinos as IceCube alone
- Detection would be strengthened by the radio method
- Not the optimal geometry for taking advantage from the acoustic method; other geometries will be investigated
- However number of radio + acoustic hybrid events similar to radio + optical one
- Still interesting to include acoustic sensors for R&D and as first step toward the bigger detector
- Triggering threshold for acoustic could be lowered to get as many coincident event as possible offline
- 1 or 2 acoustic hits in coincidence with optical or radio trigger could be statistically significant and strong evidence for neutrino event


end

Calculated acoustic radiation pattern in ice



Events by flavor (no τ)

	$\nu_e/\overline{\nu}_e$	$\nu_\mu/\overline{\nu}_\mu$	Sum
IceCube only	0.473431	1.920142	2.393573
Optical	0.851801	3.136241	3.988042
Radio	0.722941	0.952983	1.675924
Acoustic	0.121672	0.313611	0.435283
Optical + Radio	0.048182	0.049562	0.097744
Optical + Acoustic	0.013345	0.029216	0.042561
Radio + Acoustic	0.021449	0.067317	0.088766
Optical + Radio + Acoustic	0.002689	0.009241	0.01193