High energy neutrino astronomy: Principles, IceCube, beyond

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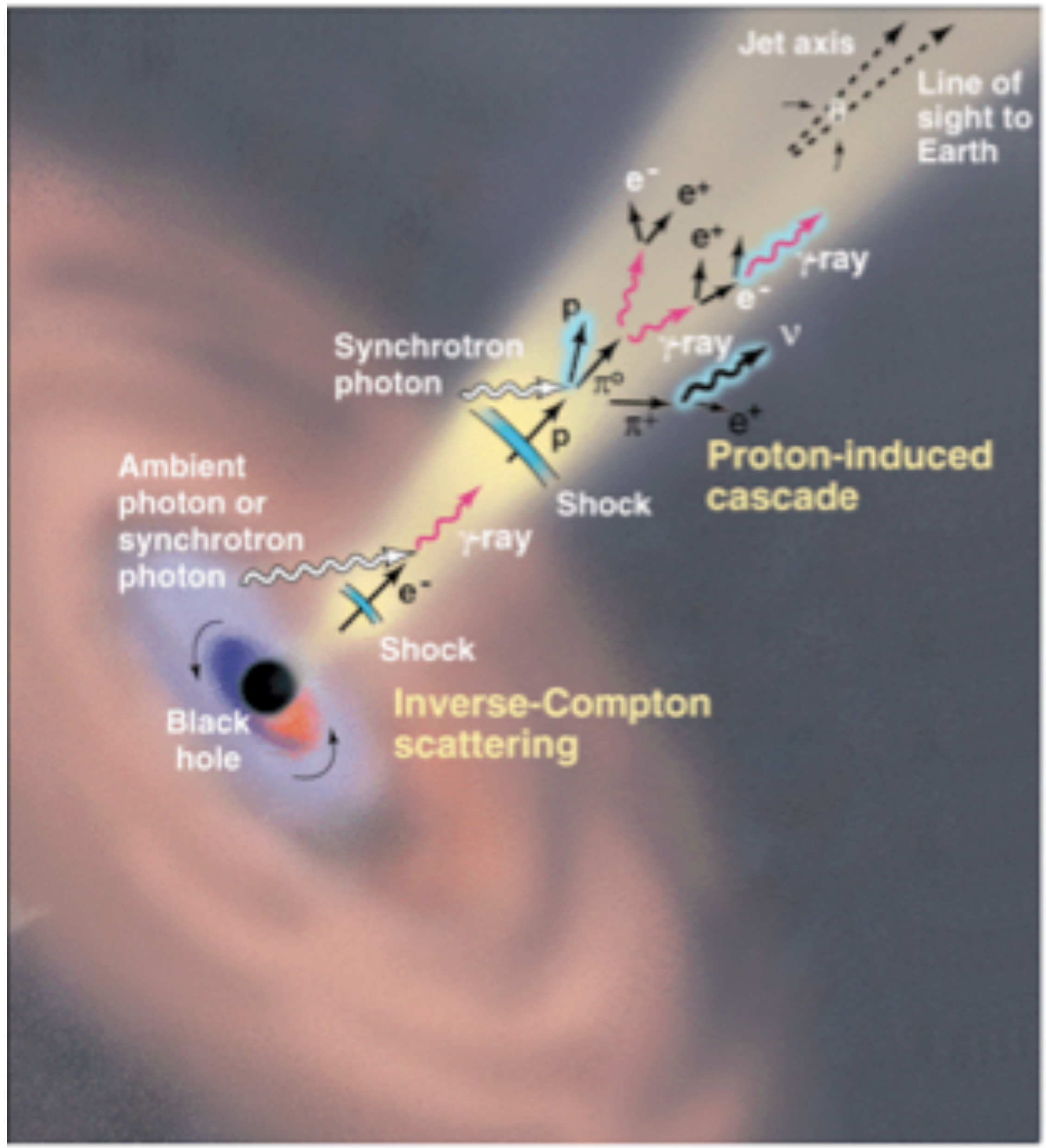
High energy particles in the Universe

What are the cosmic accelerators that generate …

- Cosmic Rays
  - Observed up to 10^21 eV
  - Mostly diffuse flux, mass composition, spectrum
- Gamma Rays
  - Observed up to ~100 TeV
  - Numerous TeV point sources resolved
- Neutrinos
  - Atmospheric neutrinos observed beyond 100 TeV



Cosmic Rays and Neutrino Sources

Candidate sources (accelerators):

Cosmic ray related:

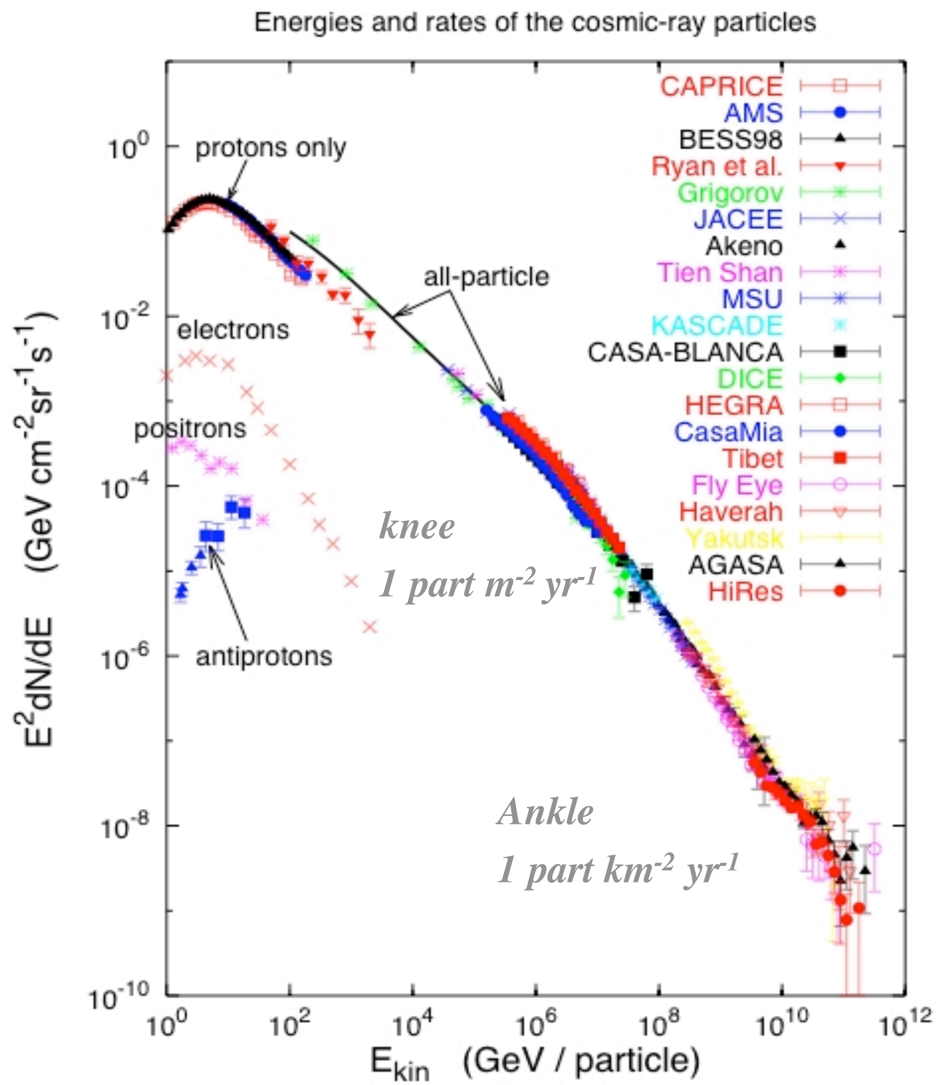
- SN remnants
- Active Galactic Nuclei
- Gamma Ray Bursts

Other:

- Dark Matter

T. Gaisser 2005

Cosmic rays

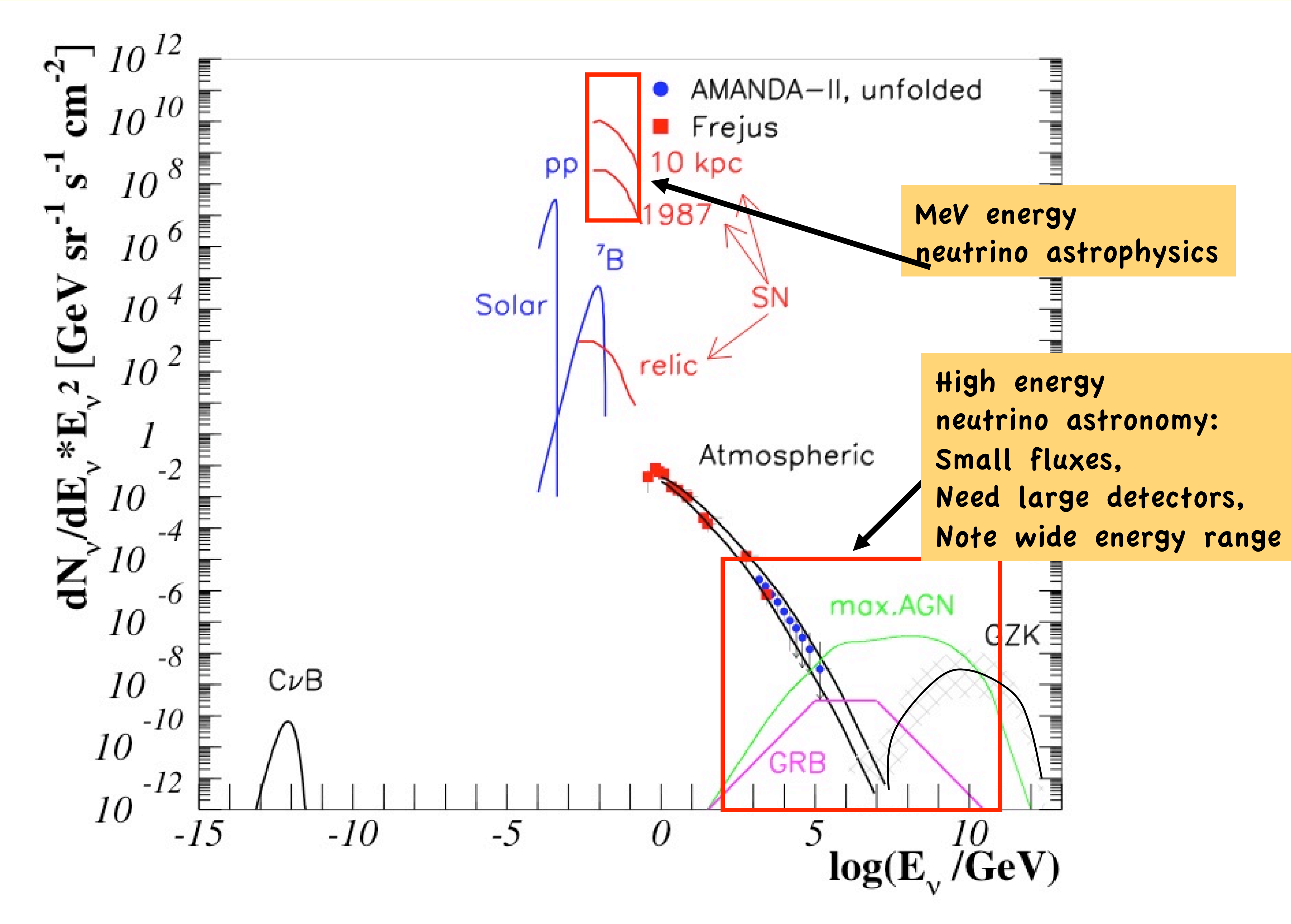


Guaranteed sources (known targets):

- Atmospheric neutrinos (from π and K decay)
- Galactic plane: CR interacting with ISM, concentrated on the disk
- GZK (cosmogenic neutrinos)

$p\,\gamma \rightarrow \Delta^{+} \rightarrow n\,\pi^{+}\ (p\,\pi^{0})$

Neutrinos


AMANDA−II, unfolded
Frejus
10 kpc
1987
pp
Solar
7B
SN
relic
Atmospheric
max.AGN
GZK
GRB
CνB
$dN_\nu/dE_\nu*E_\nu^2$ [GeV sr^{-1} s^{-1} cm^{-2}]
log(E_ν /GeV)
MeV energy
neutrino astrophysics
High energy
neutrino astronomy:
Small fluxes,
Need large detectors,
Note wide energy range

Universe is not transparent for HE photons or nuclei!

$\gamma + \gamma_{CMB} \rightarrow e^+ + e^-$

$p + \gamma_{CMB} \rightarrow \Delta^+ \rightarrow n + \pi^+$

$\mu^+ + \nu_\mu$

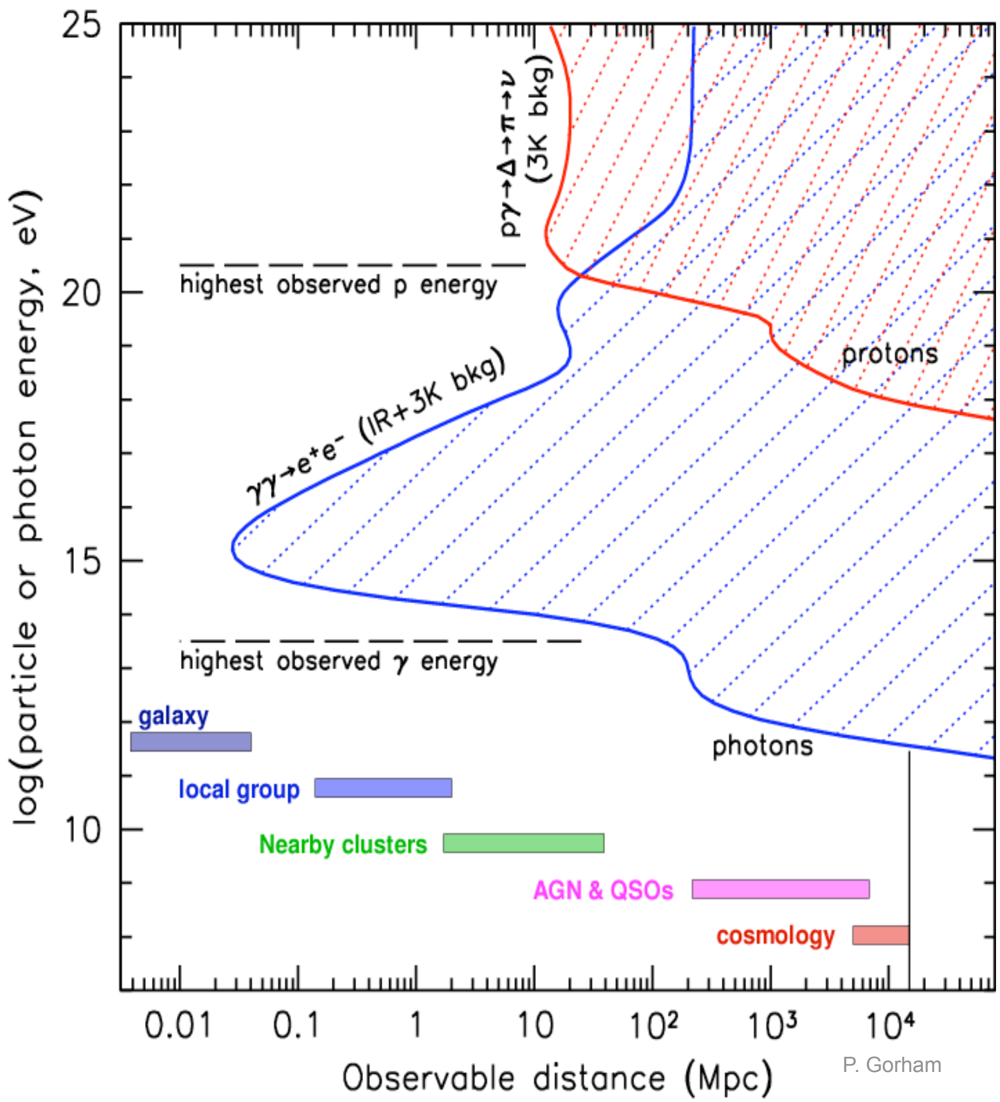
GZK - neutrinos

Protons deflected by magnetic field for

$E < 10^{19}$ eV!

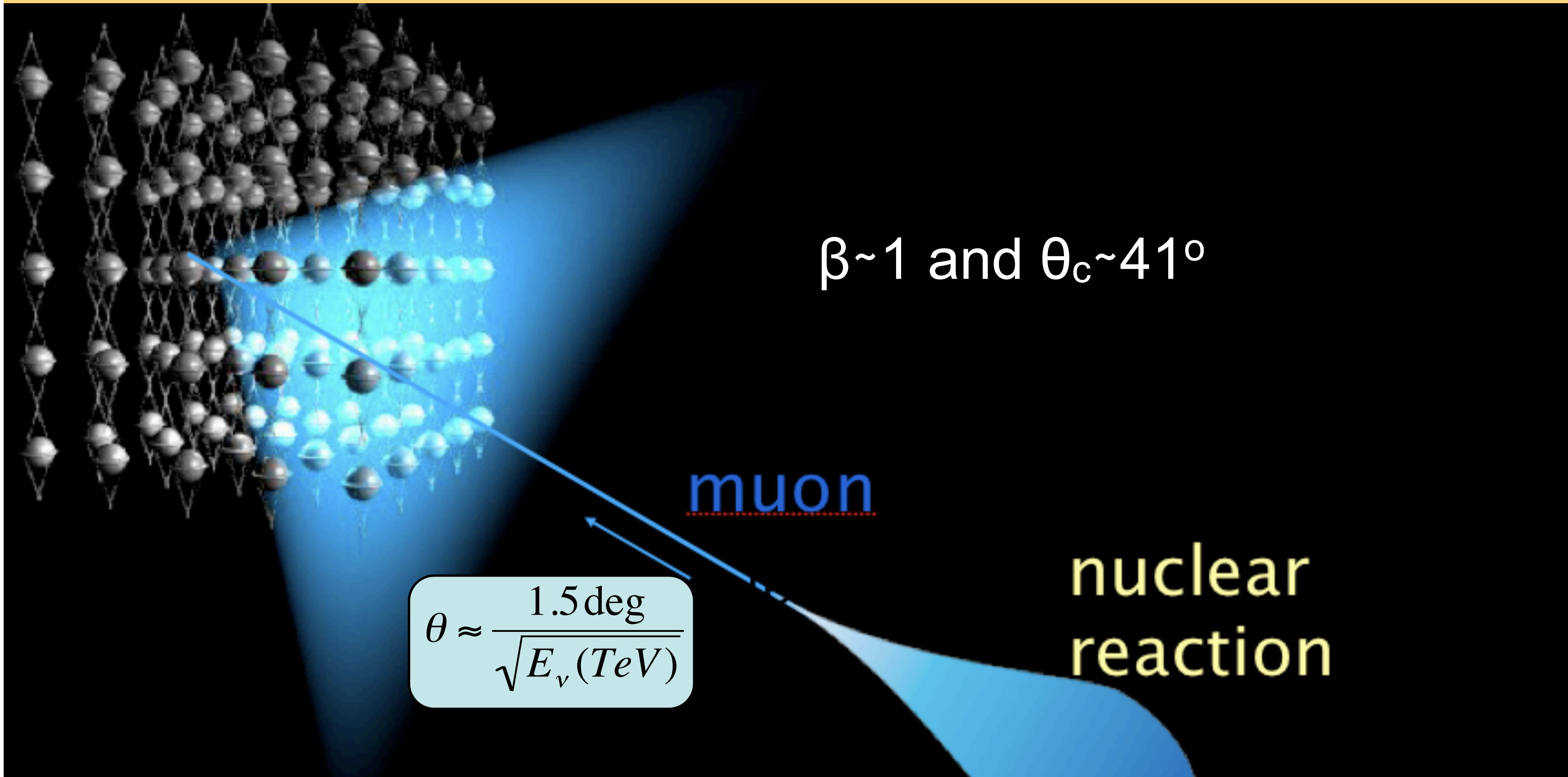
Not pointing back to the source!

Need neutrinos for high energy (>10TeV) cosmic astronomy!



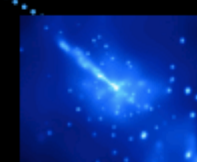
P. Gorham

Concept of large neutrino telescopes



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 2* 10^4 Cherenkov photons/m of a muon track
Perfect scaling with dE/dx as radiative losses increase above 10 TeV



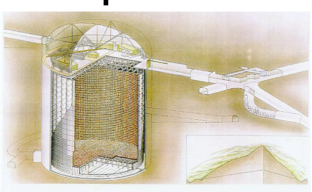
Deep water Cherenkov neutrino detectors

Low energy underground neutrino detectors provide important experiences and results (Frejus, MACRO, IMB, Kamioka, SuperK, SNO, ….)

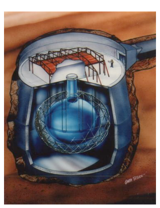
Telescopes for TeV energies:

- First envisioned by Greisen, Markov 1960
- Pioneering effort: DUMAND near Hawaii
- First and second generation telescopes in 90's, proof of principle : Baikal, AMANDA (S Pole), NESTOR (Greece).
- Current generation experiments and initiatives:
  - 50000m^2 scale: ANTARES, AMANDA (integrated in IceCube),
  - km scale: IceCube (running at ~50% size)
- Next generation:
  - IceCube almost complete (go from 59 to 86 strings by 2011)
  - Based on NESTOR, NEMO, ANTARES experiences→ km3NeT project, Mediterranean Sea.

Super-K

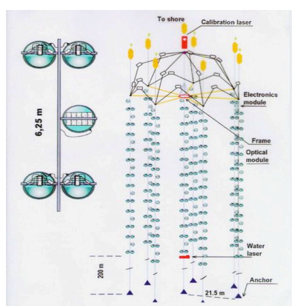


Not to scale!

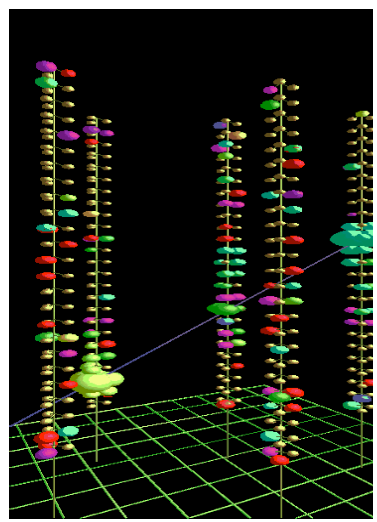


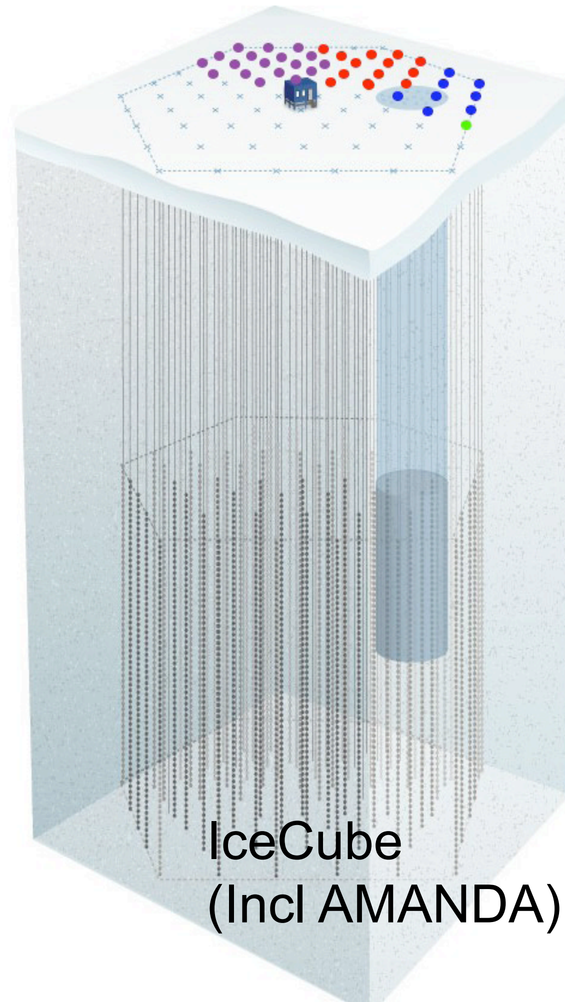
SNO

Baikal



ANTARES



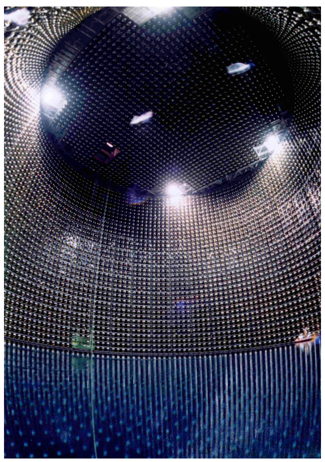


IceCube (Incl AMANDA)

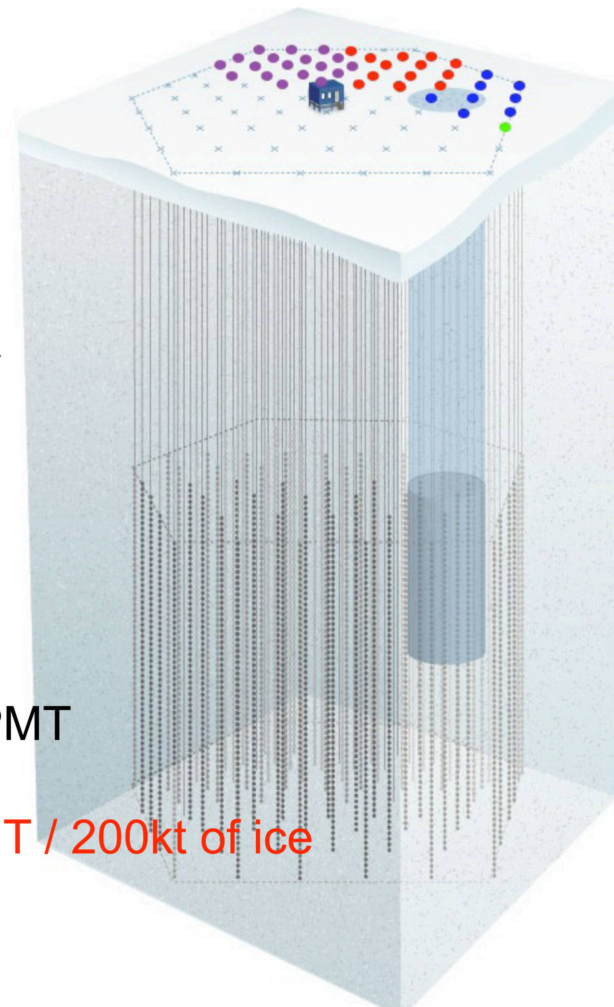
Albrecht Karle, UW-Madison

Maximize size of detector
large spacing of PMT

- Challenge: maximize PMT spacing to maximize detector volume



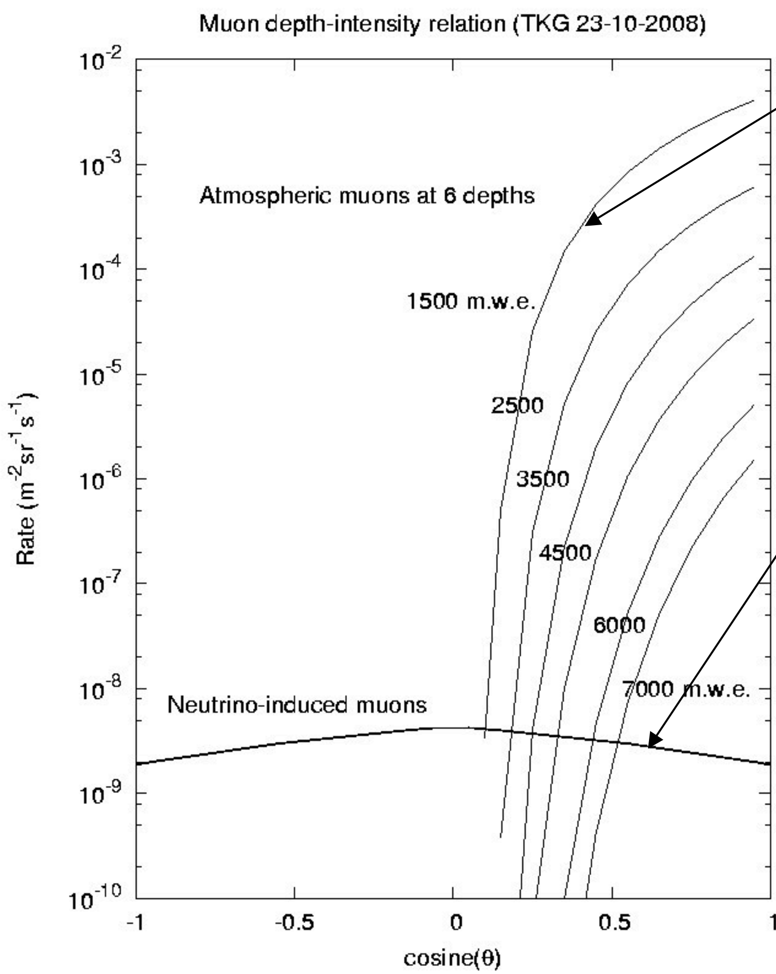
PMT Cathode/unit mass:~10^-5



Super-K
11000 x 50cm PMT
50kt
One 50 cm PMT/5t

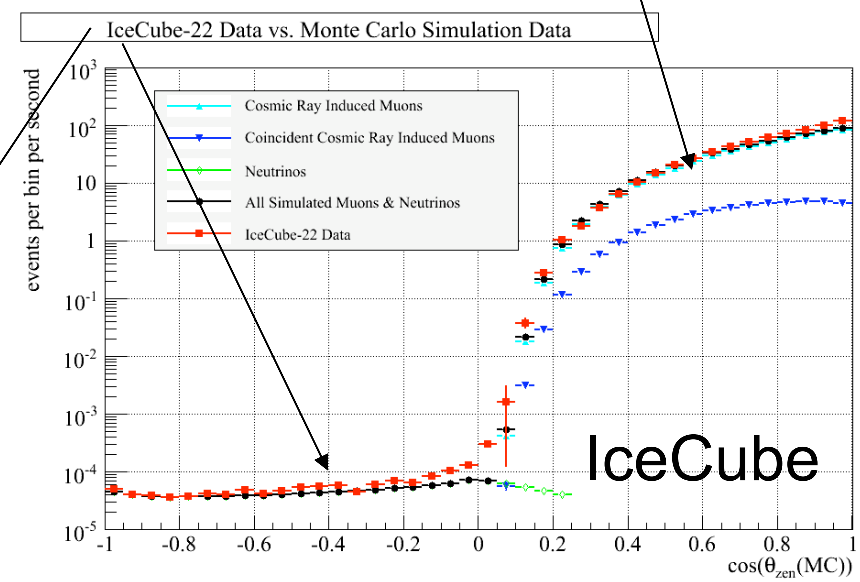
IceCube
5000 x 25cm PMT
1000 Mt
One 20 cm PMT / 200kt of ice

Muons in ν telescopes



Downward atmospheric muons

Neutrino-induced muons
from all directions



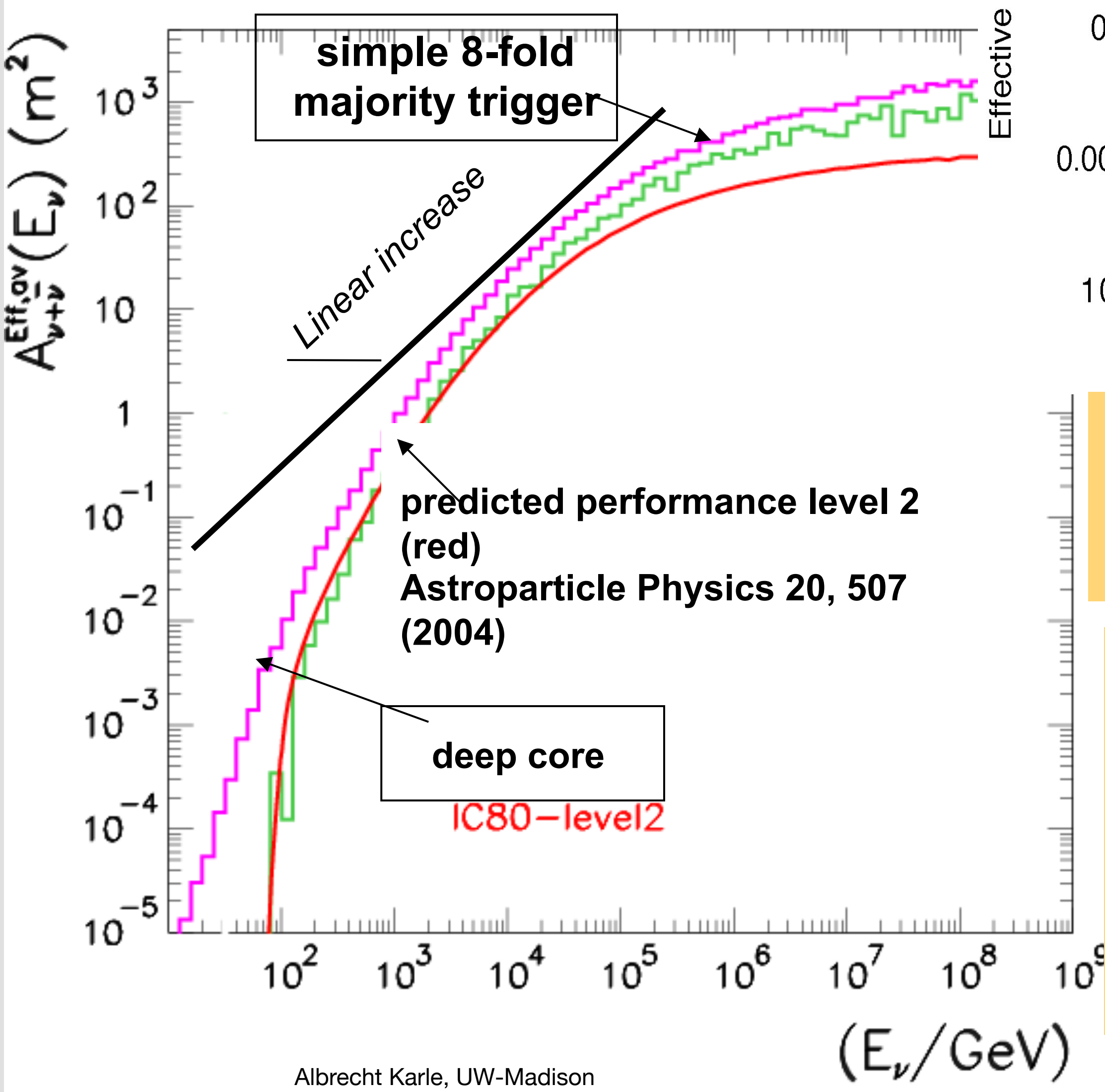
Patrick Berghaus et al., Cosmo-08
and ISVHECRI-08

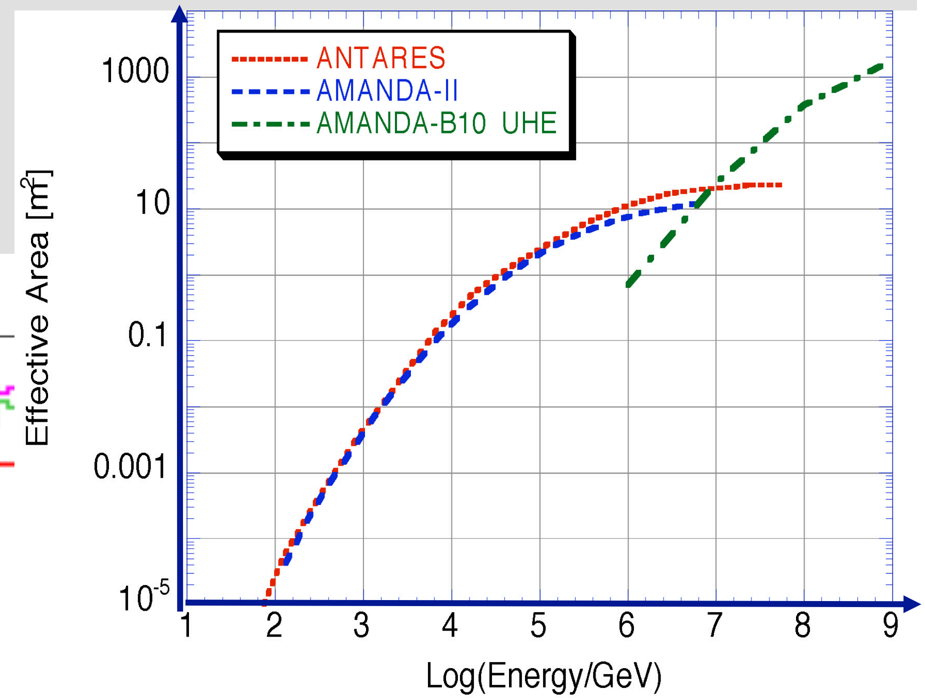
Depending on depth BG/neutrino ratio: 10^3 (6000mwe) to 10^8 (1000mwe)

→Low energies: Use Earth as filter; look for neutrinos from below (GeV to PeV)

→High energies: Apply energy cut for downgoing atmospheric background (>PeV)

Neutrino effective areas IceCube





Area at 100 TeV (1TeV)
AMANDA-II: $3m^2$ (0.005)
IceCube 86: $100m^2$ (0.3)

- Effective area for ν_μ

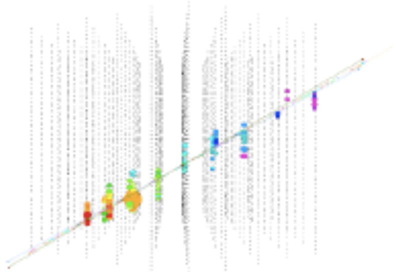
$$A_{eff}^{\nu} = \sigma \otimes P_{Earth} \otimes R_\mu \otimes \varepsilon_{eff}$$

- Strong rise with energy:
  - $\sigma \propto E_\nu$
  - Increase of muon range with energy

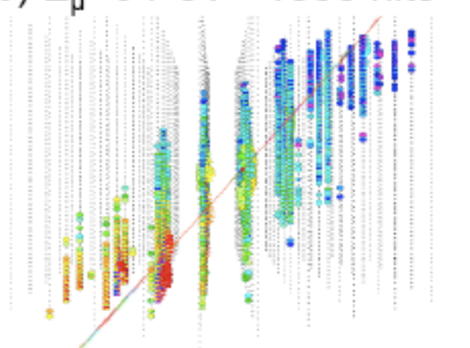
Neutrino Topologies

Muon neutrino

a) E_μ=10 TeV ~ 90 hits



b) E_μ=6 PeV ~1000 hits



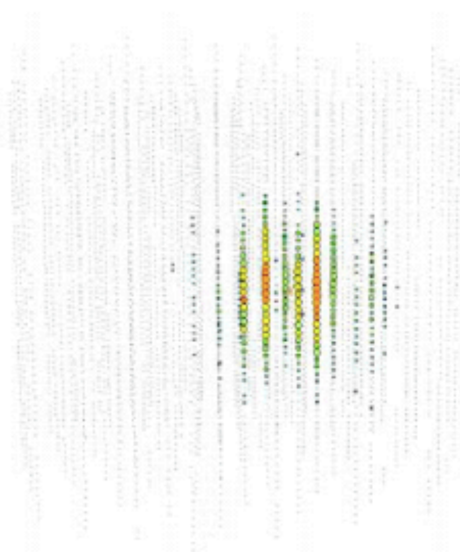
E ~ dE/dx, E> 1 TeV

Energy Res. : log(E)~0.3

Angular Res.: 0.8 -2 deg

Electron neutrino

E = 375 TeV

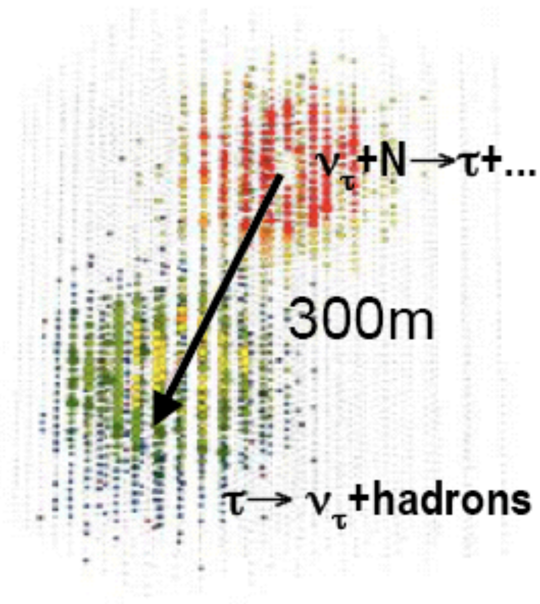


Energy Res. log(E)~0.1-0.2

Poor Angular Resolution

Tau neutrino

E = 10 PeV



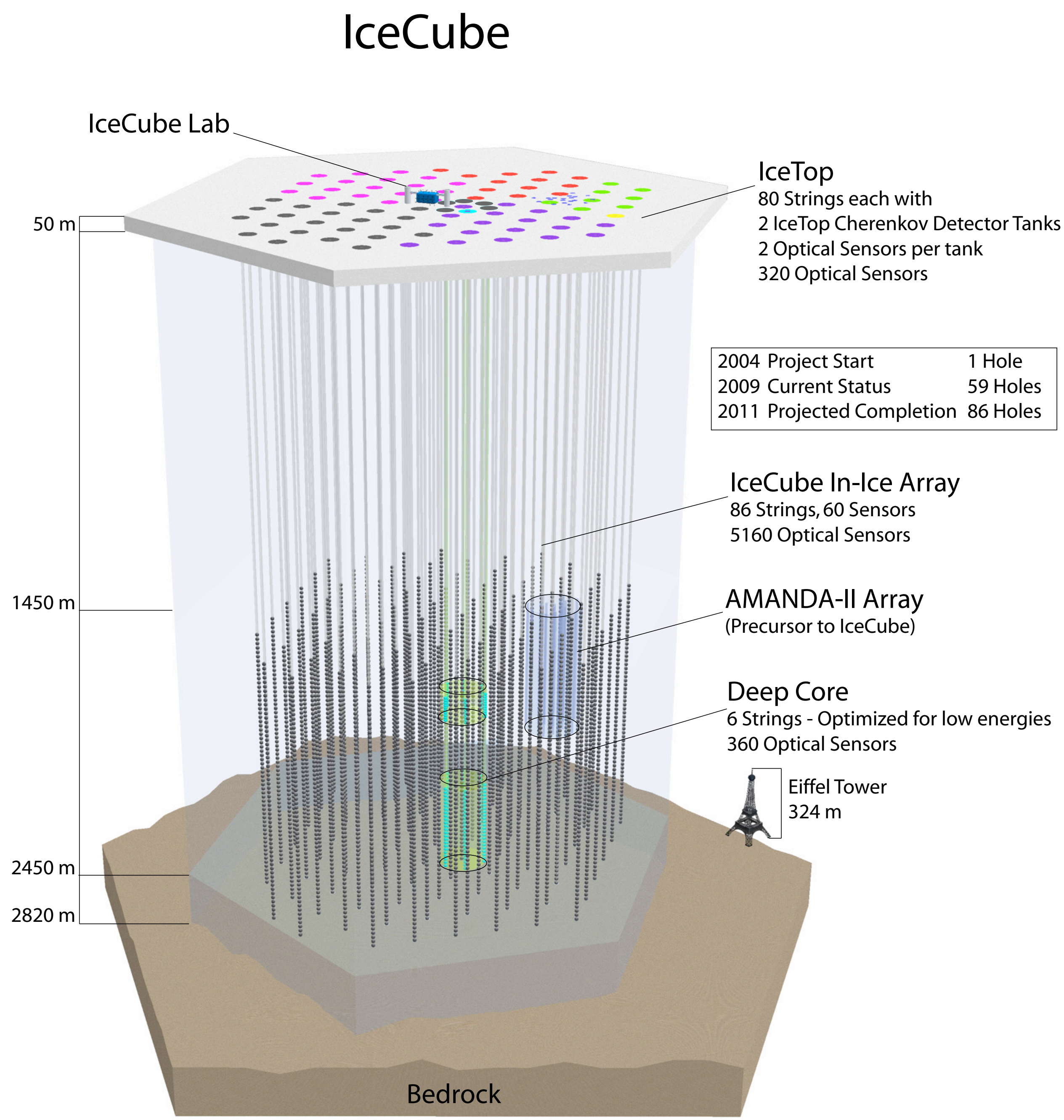
Double-bang signature above ~ 1 PeV

Very low background

Pointing capability

Best energy measurement

- Total of 59 strings and 118 IceTop tanks → over two thirds complete!
- Completion with 86 strings by 2011
- Detector is taking data during construction phase.



The IceCube Collaboration

USA:

Bartol Re
Universit
Universit
Pennsylv
Clark-Atl
Ohio Sta
Georgia T
Universit
Universit
Universit
Universit
Lawrenc
Universit
Southerr
College
Universit

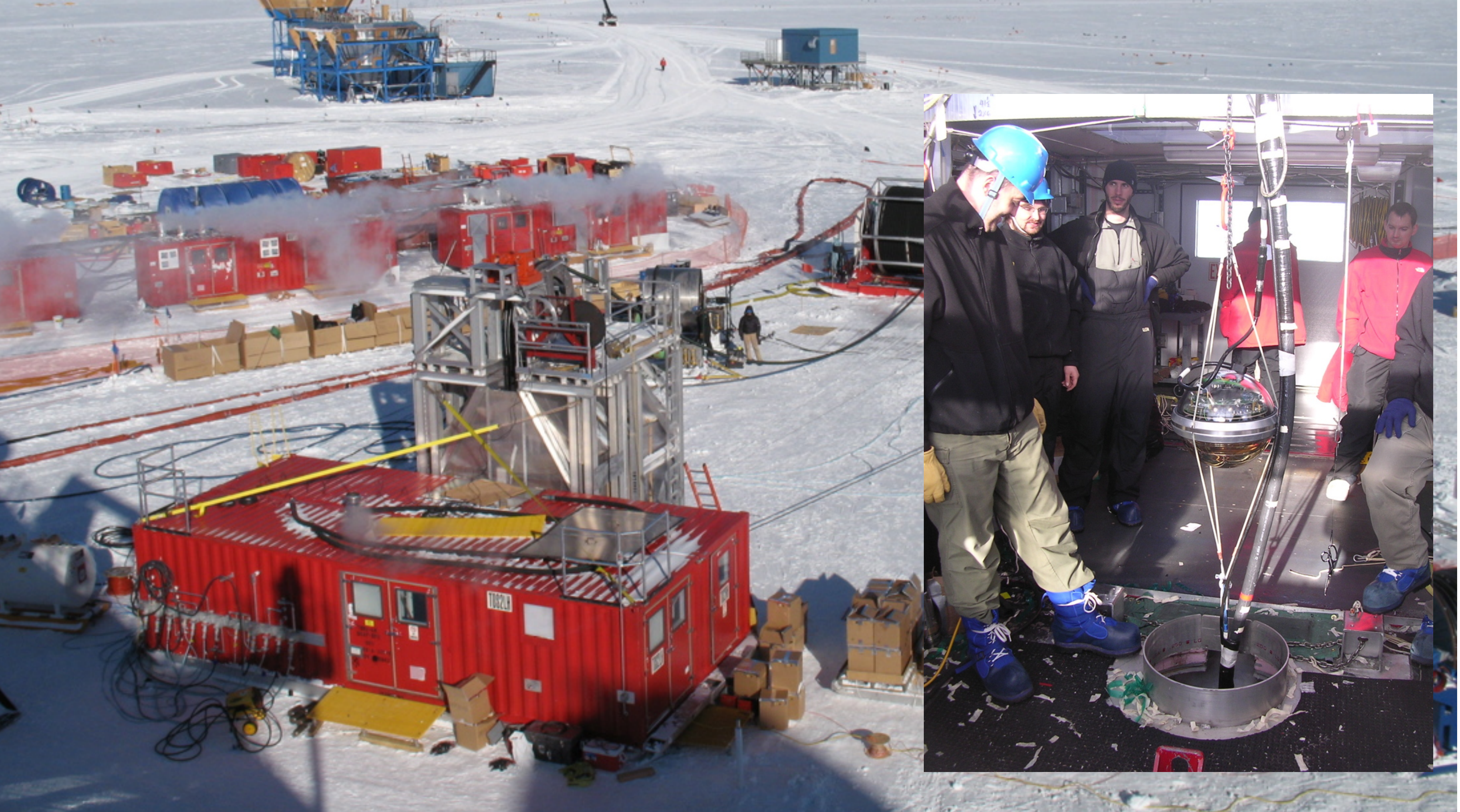
ersity

bury

33 institutions, ~250 members
http://icecube.wisc.edu

IceCube Construction site

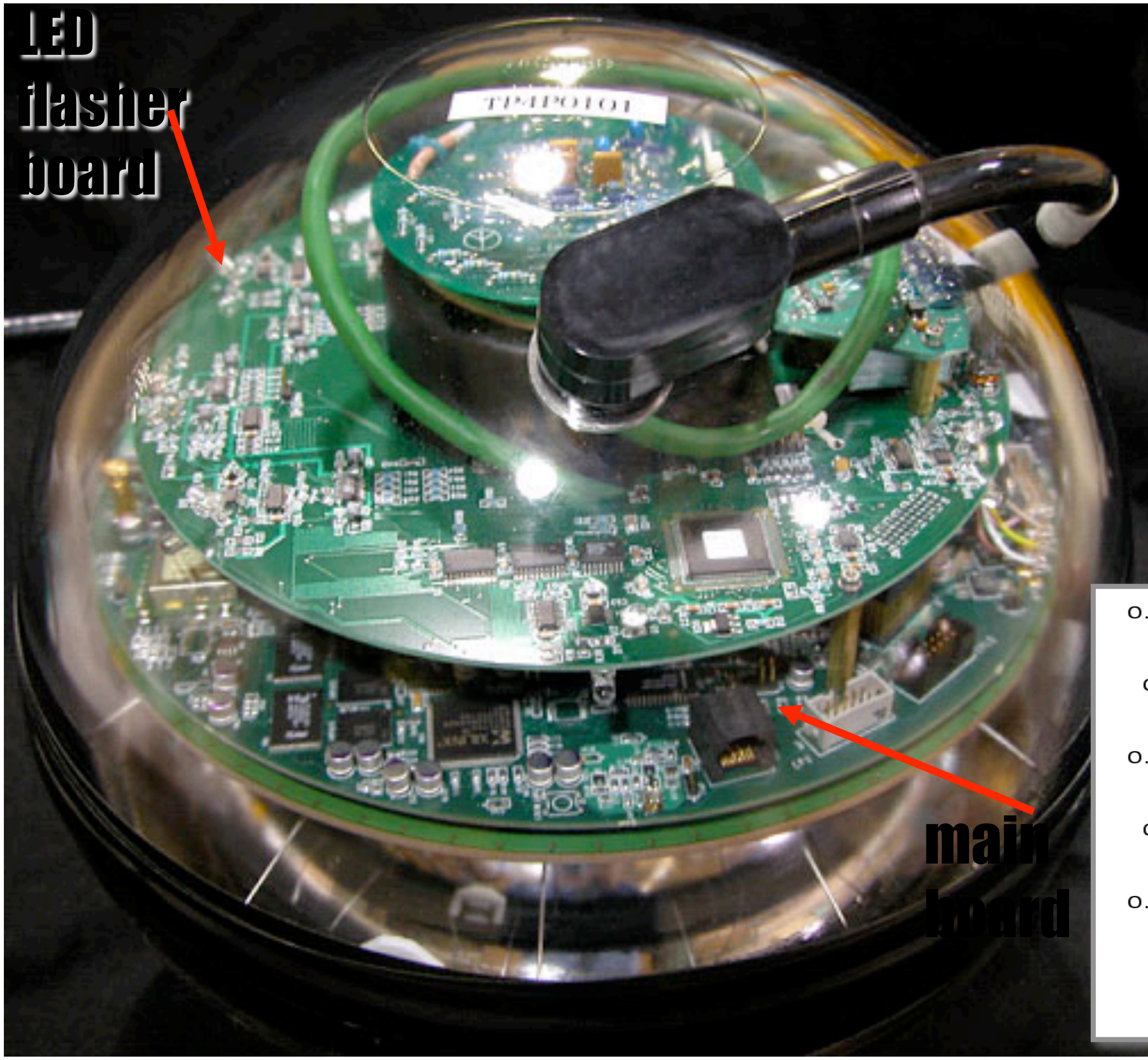
- Hotwater drill
- Thermal power: 5 MW
- 60 cm diameter hole, 2m/min
- Time to complete: 35 hrs
- Time between two strings: ~50h



IceCube: Digital Optical Module (DOM)

Local digitization and time stamping
(common requirement to all large detectors)

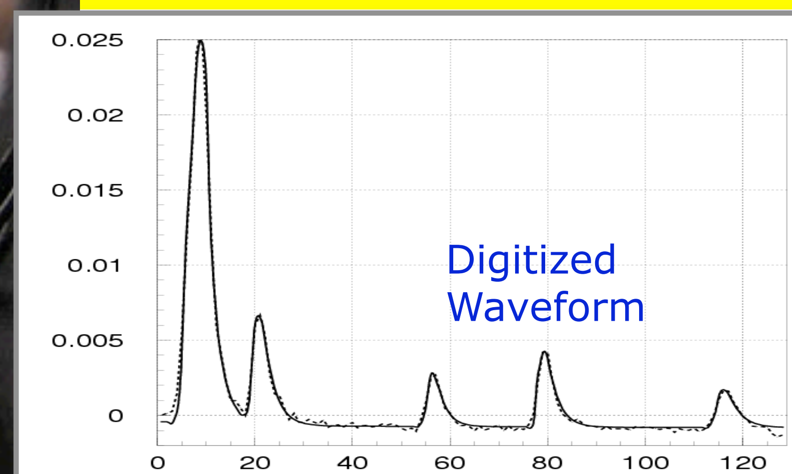
Design for high reliability!
Detectors are not accessible



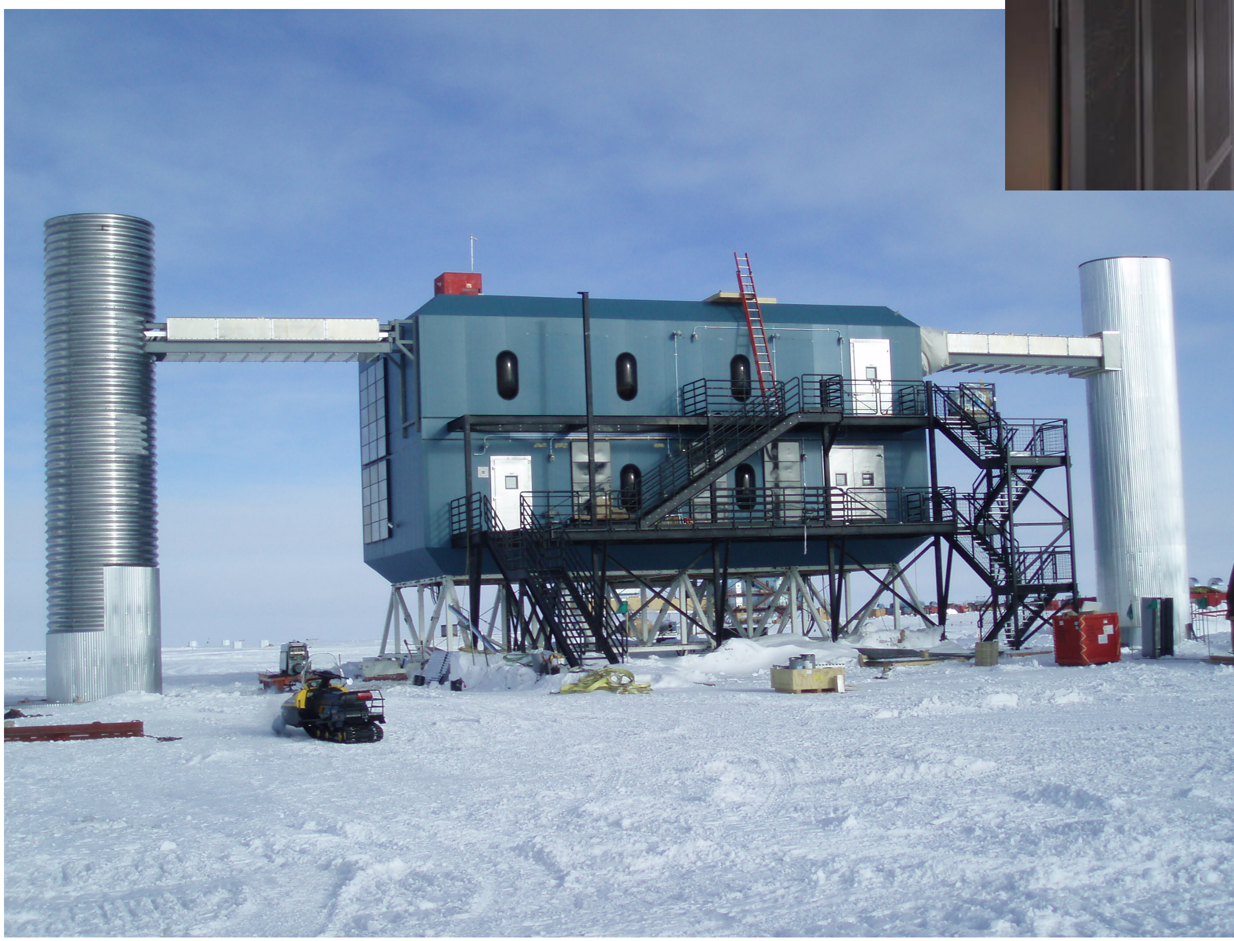
PMT: 10 inch Hamamatsu
Power consumption: 3 W
Digitize at 300 MHz for 400 ns with custom chip
40 MHz for 6.4 μs with fast ADC
Dynamic range 500pe/15 nsec

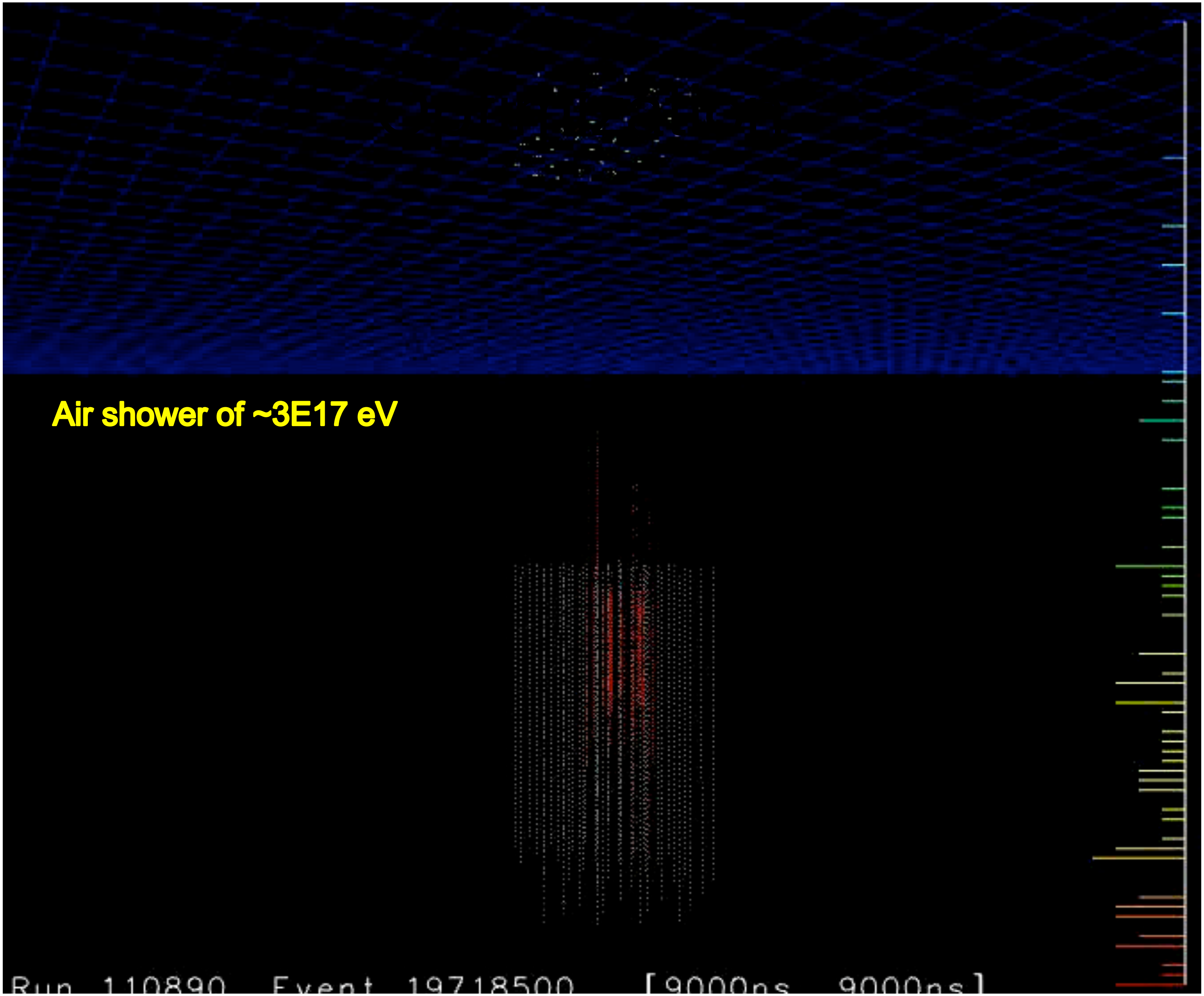
Send all data to surface over copper
2 sensors/twisted pair.
Flasherboard with 12 LEDs
Local HV

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

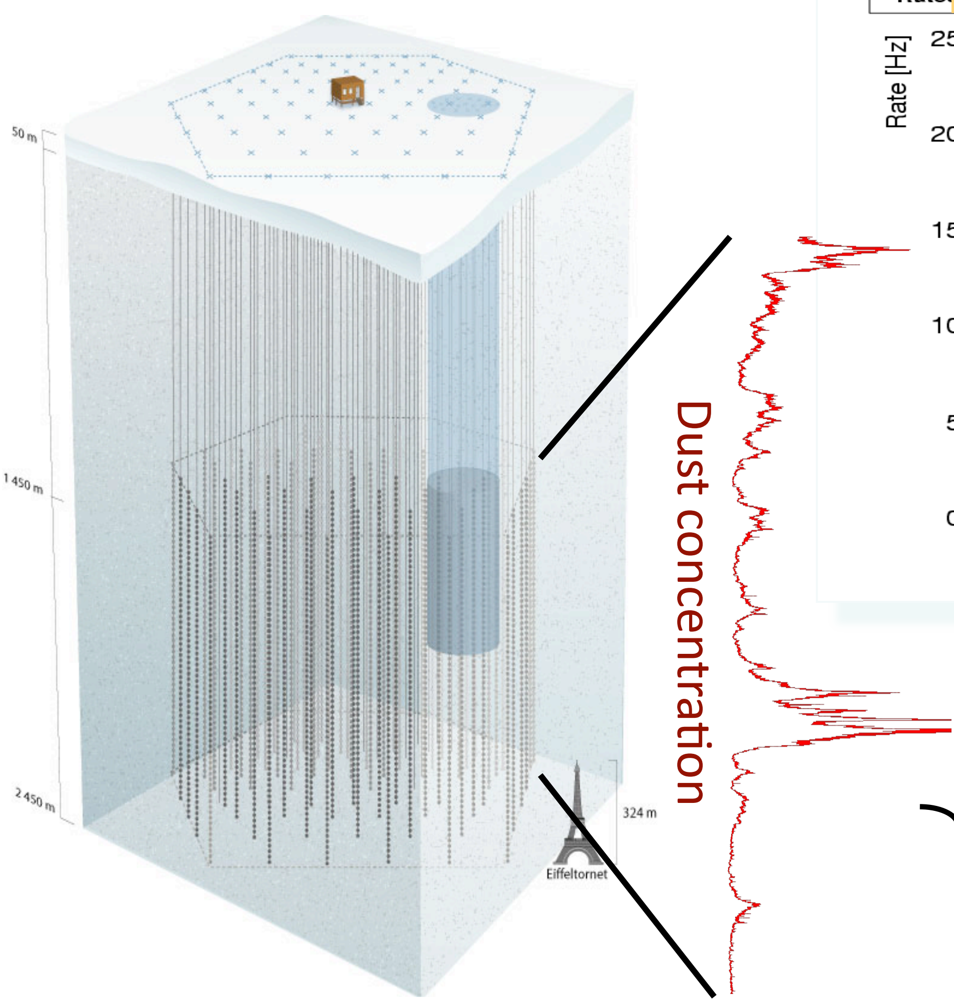


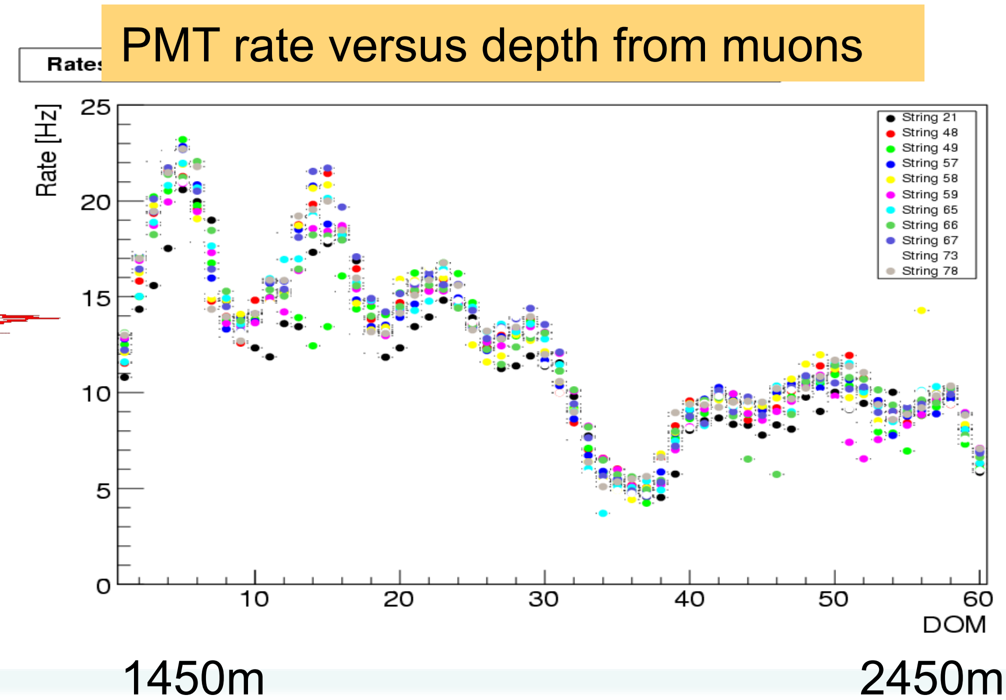
ICL: IceCube Laboratory and Data Center



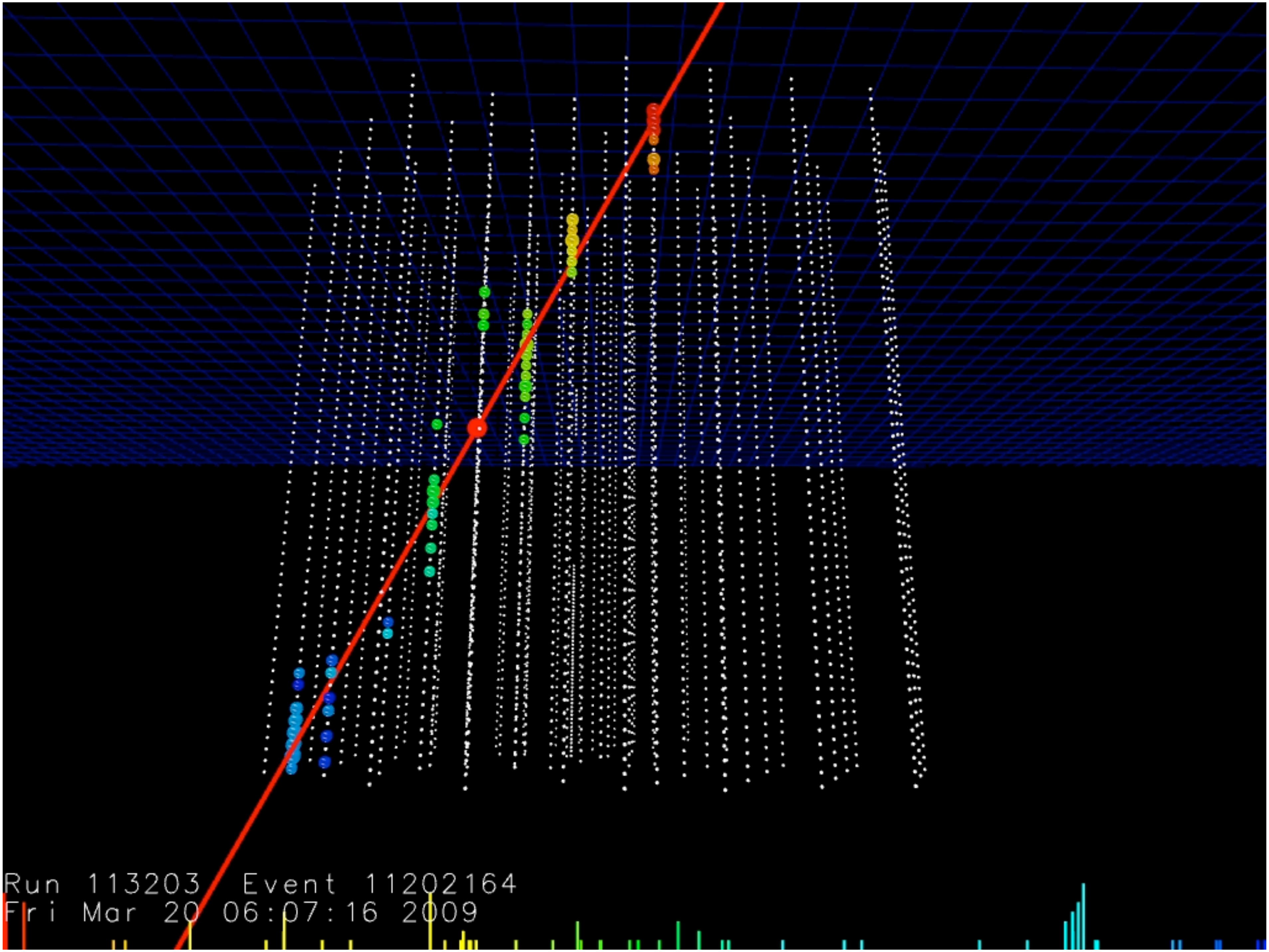

Air shower of ~3E17 eV
Run 110890 Event 19718500 [9000ns 9000ns]

Understand and model optical properties of Ice





Very clear ice

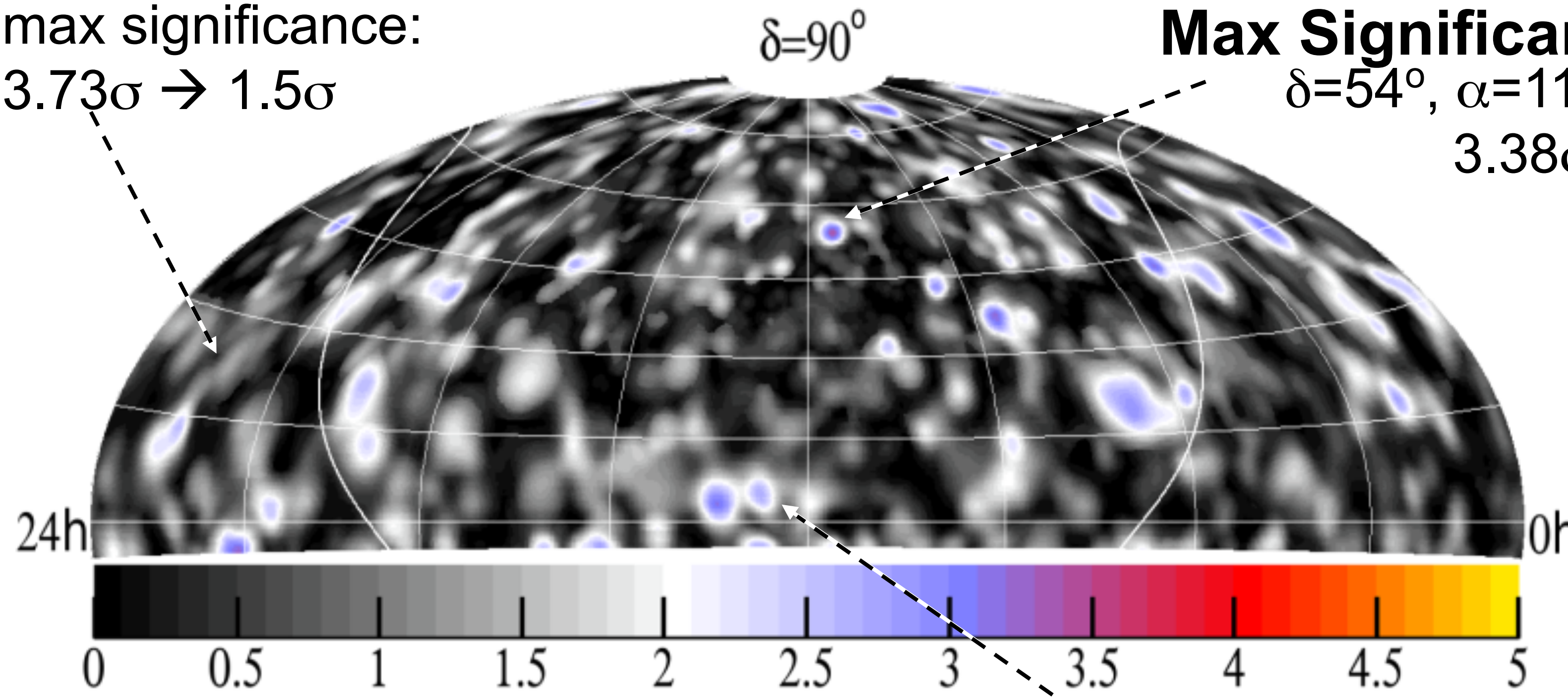


Run 113203 Event 11202164
Fri Mar 20 06:07:16 2009

Skymap of 7 years of AMANDA-II

3yr max significance:
3.73σ → 1.5σ

Max Significance
δ=54°, α=11.4h
3.38σ



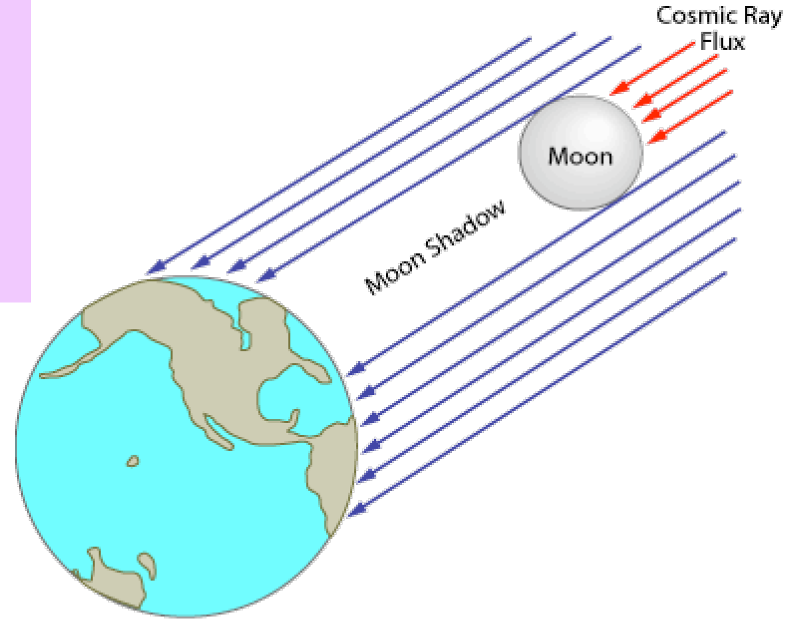
Significance

5yr max significance:
3.74σ → 2.8σ

R. Abbasi et al., Phys. Rev. D 79, 062001 (2009).

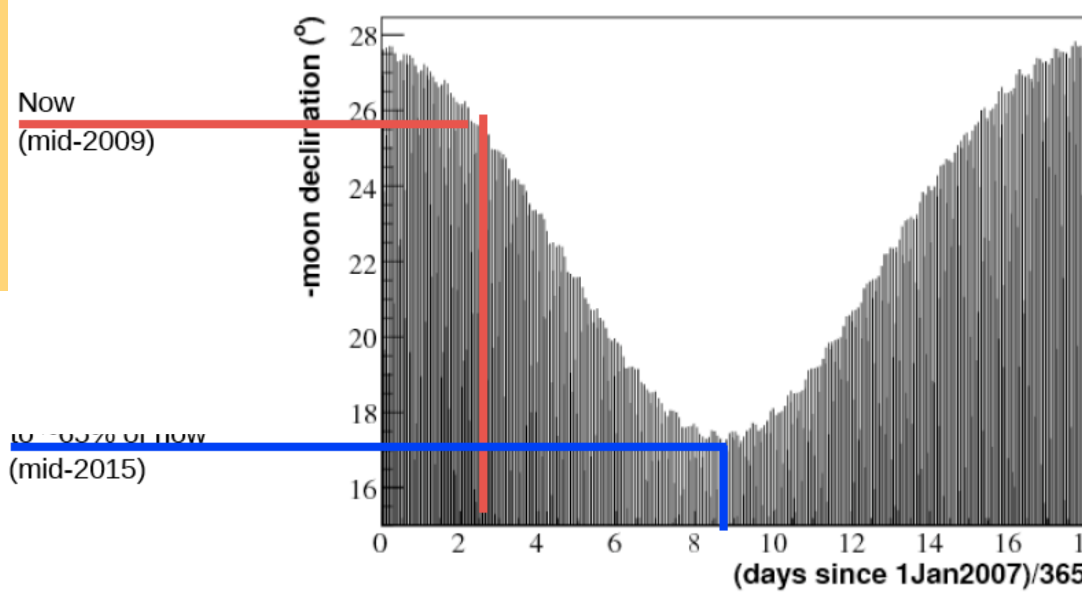
95 of 100 data sets randomized in RA have a significance ≥ 3.38σ
→ No signal

Moon shadow seen in cosmic ray muons with 40 strings of IceCube



Gladstone et al, APS spring meeting 2009
(also Cosmo 08)

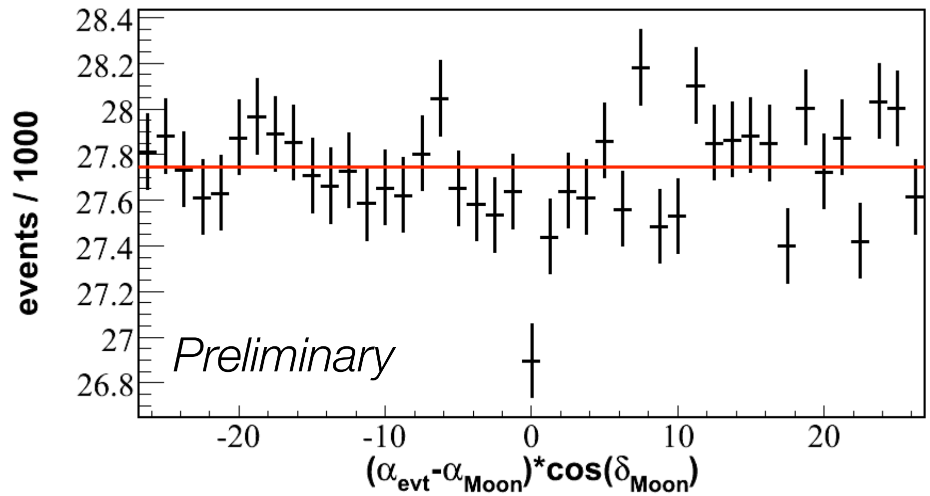
8 months of IC40 data
0.7° radius bins around Moon position
Check of absolute positioning and coordinate transformations

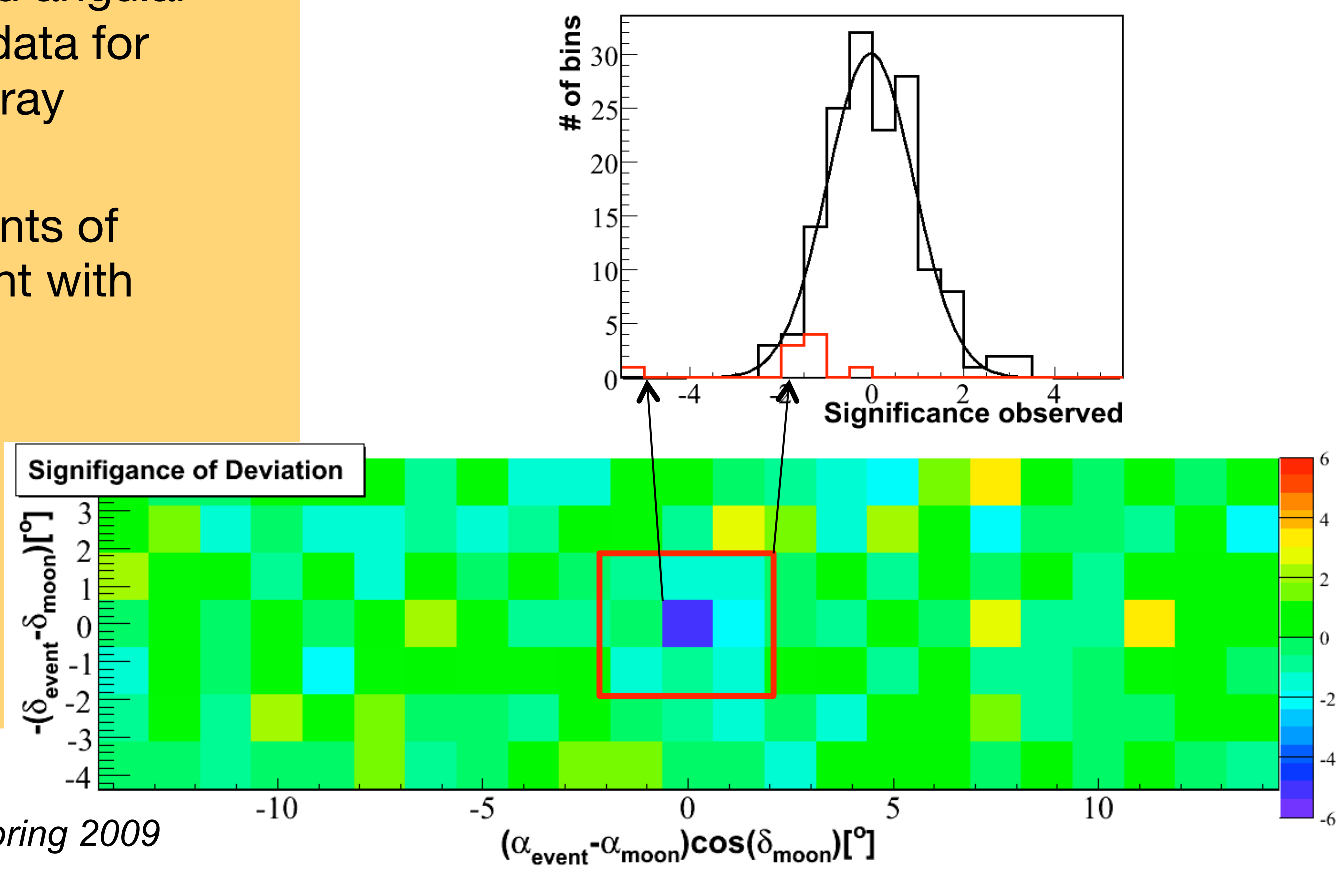


Moon shadow observed in muons

Preliminary

- Moon reaches an altitude of 28° at the South Pole (2008)
- Despite large zenith angle, sufficient statistics and angular resolution to analyze data for shadowing of cosmic ray primaries.
- Deficit: 5 σ (~900 events of ~28000) and consistent with expectation.
- IceCube works!
- More statistics will allow study of angular response function



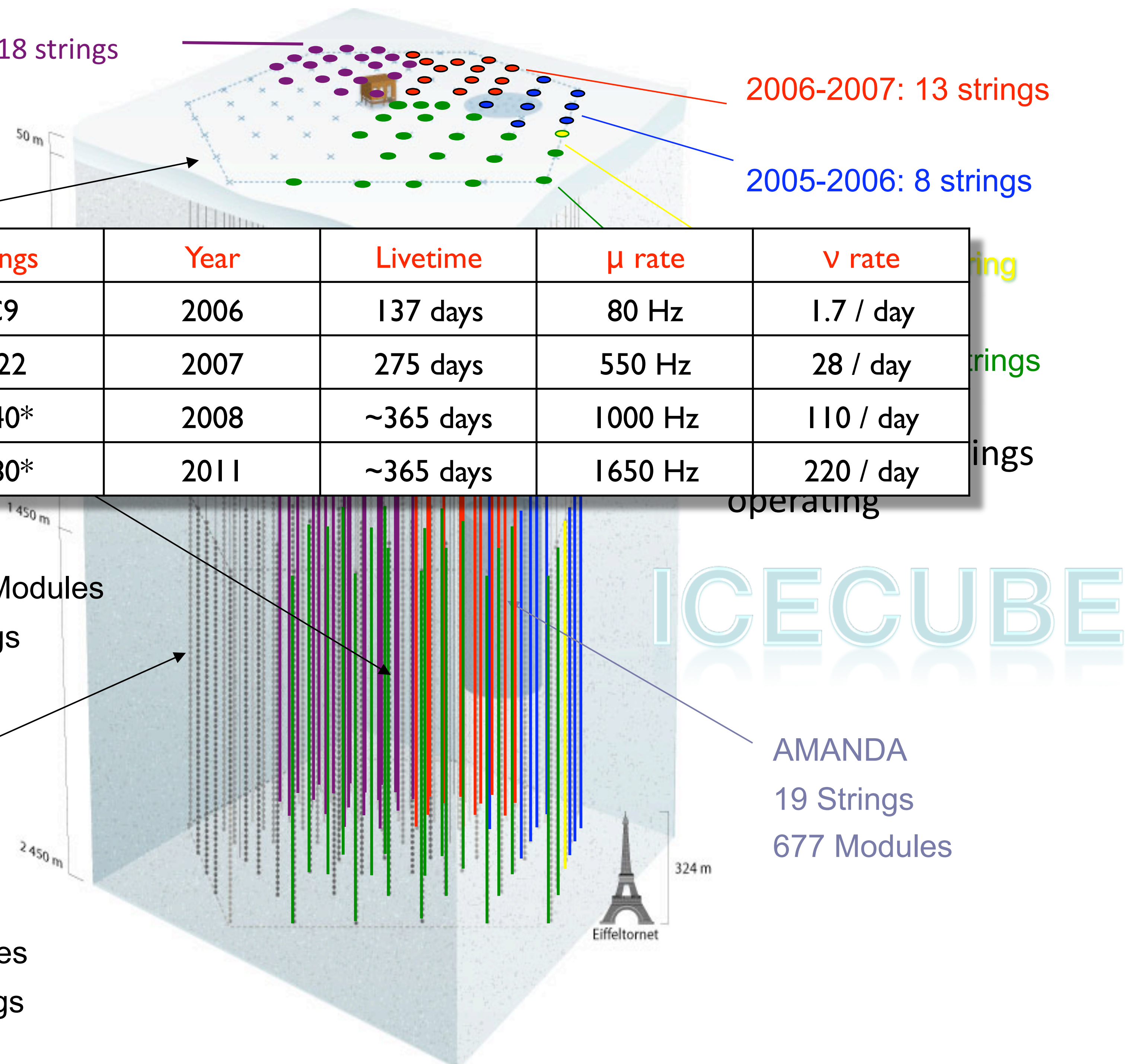


Gladstone et al. APS meeting, spring 2009

IceTop

Air shower d

threshold ~



Strings	Year	Livetime	μ rate	ν rate
IC9	2006	137 days	80 Hz	1.7 / day
IC22	2007	275 days	550 Hz	28 / day
IC40*	2008	~365 days	1000 Hz	110 / day
IC80*	2011	~365 days	1650 Hz	220 / day

DeepC

6 additional

60 Optical Modules

7 or 10 m between Modules

72 m between Strings

InIce

70-80 Strings ,

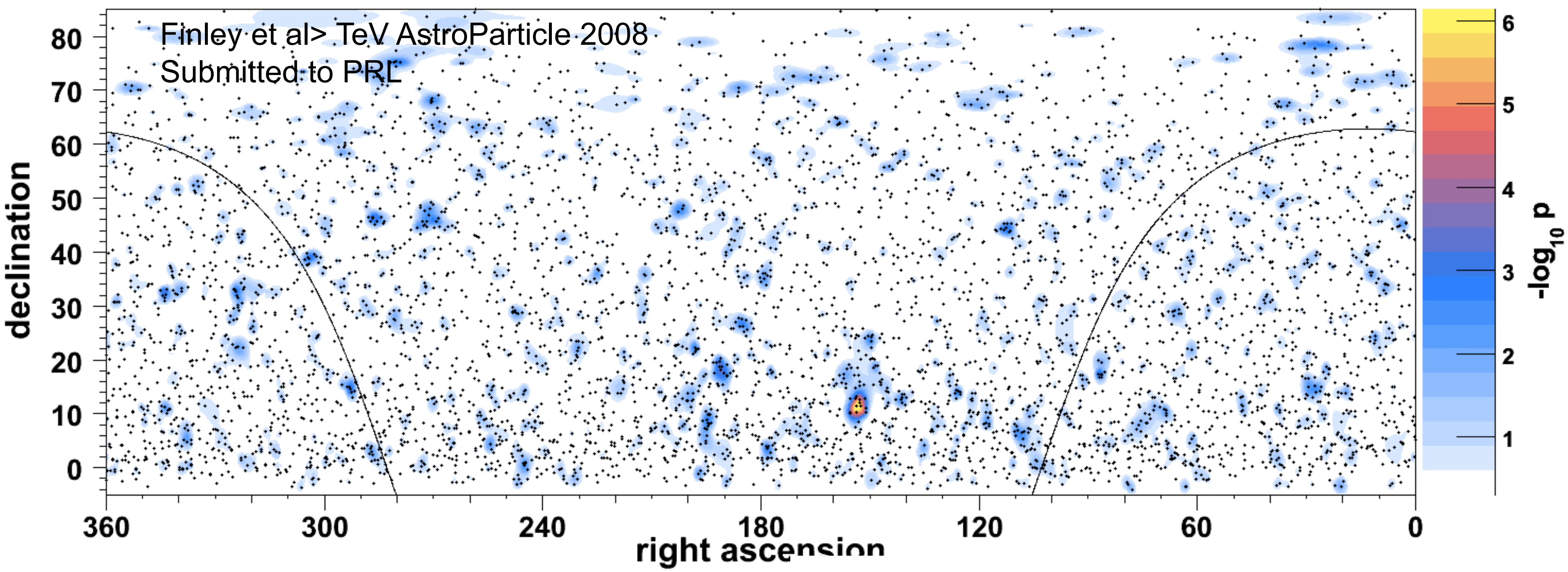
60 Optical Modules

17 m between Modules

125 m between Strings

Pointsource search

Sky map with first 22 strings of the IceCube detector



5114 neutrino candidates in 276 days livetime!

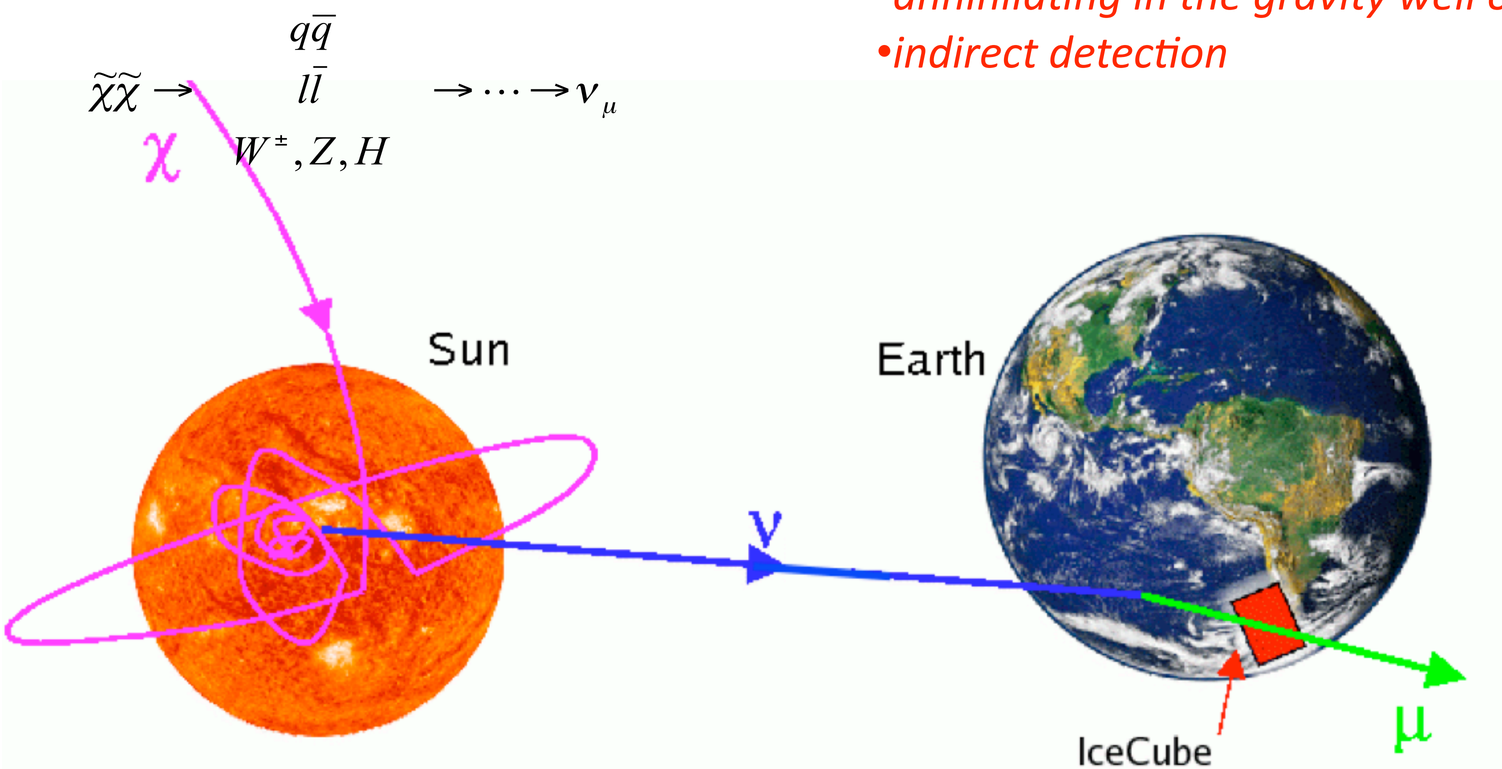
$$\mathcal{S}_i = \frac{1}{2\pi\sigma_i{}^2} e^{-r_i{}^2/2\sigma_i{}^2} \cdot P(E_i|\gamma)$$

energy variables used
Most significance comes from few HE events.

Hottest spot found at r.a. 153º , dec. 11º
pre-trial p-value: 7x 10^{-7} (4.8 σ)
est. nSrcEvents = 7.7 est. γ = 1.65
Accounting for all trials, p-value for analysis is 1.34% (2.2 σ).
At this significance level, consistent with fluctuation of background.

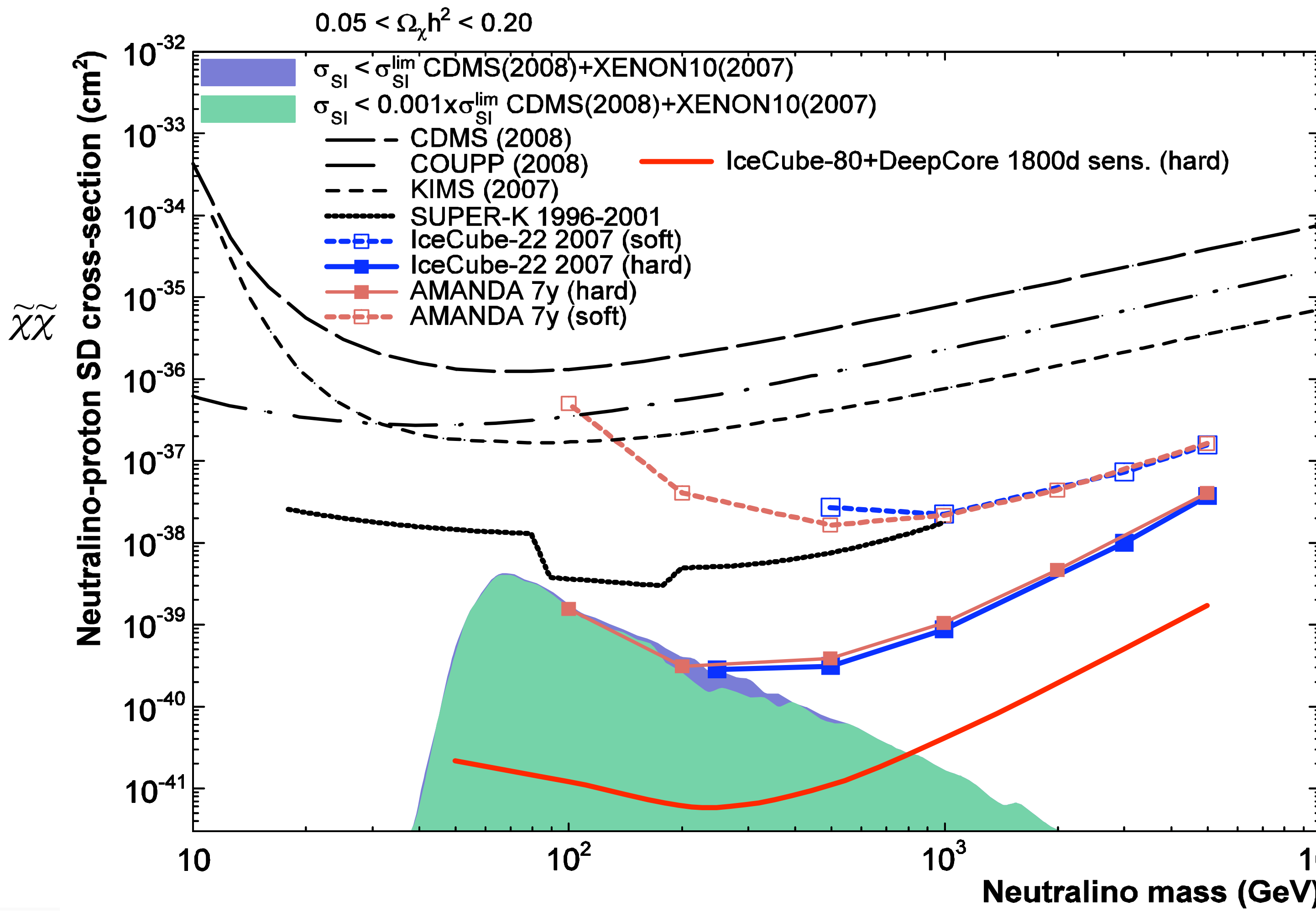
Search for dark matter, example: WIMPs in sun → neutrino flux at Earth

•annihilating in the gravity well of the Sun
•indirect detection



•See astro-ph 0903.2986 (Wikstrom and Edsjo) for method of converting muon flux to cross section limit.

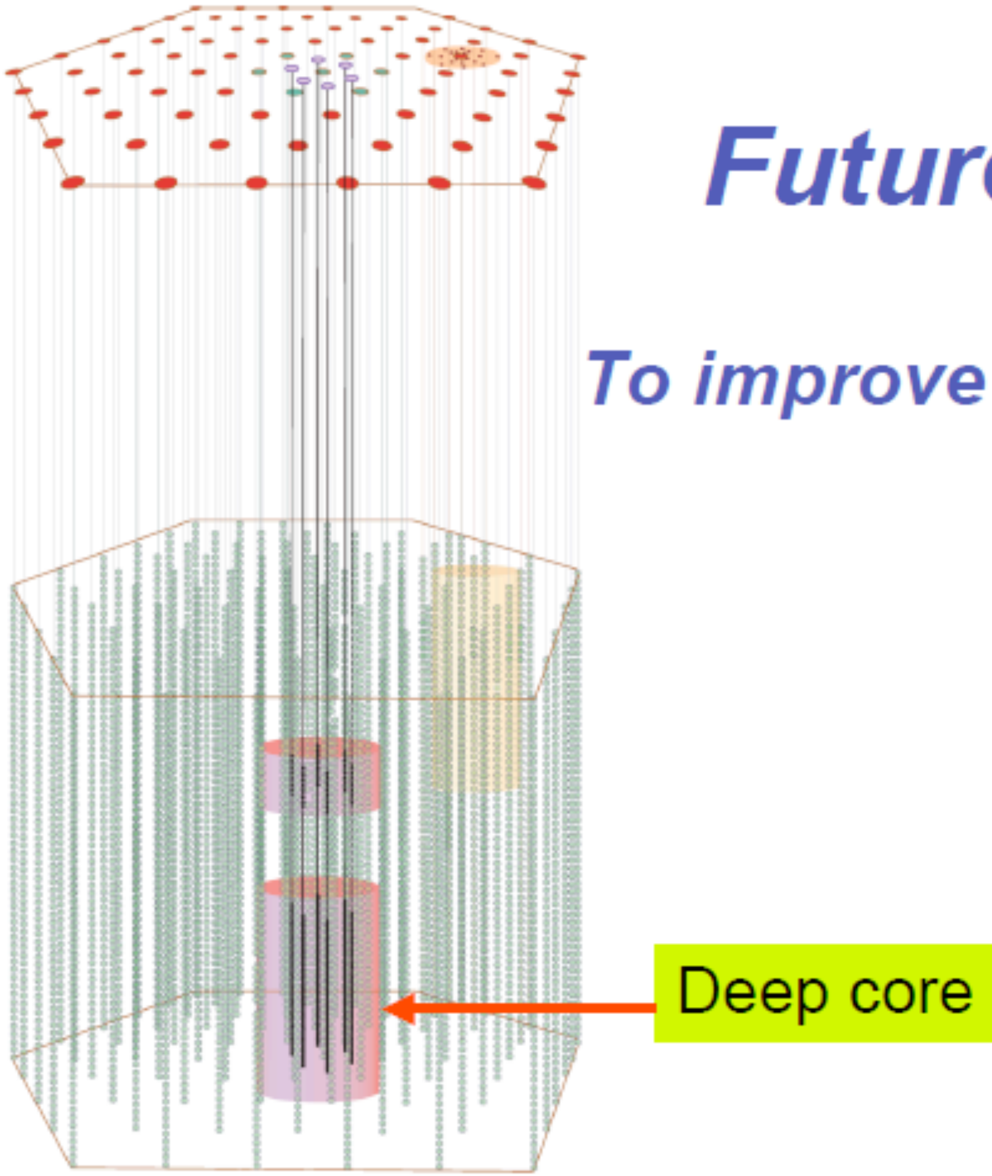
Dark Matter
example: search for neutrinos from WIMP annihilation in the sun



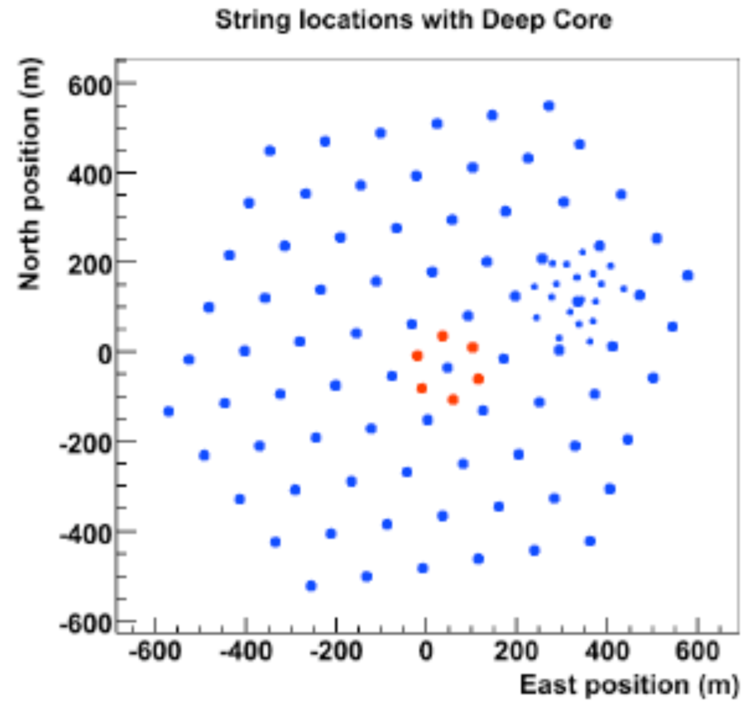
→ Deep core enhancement under construction will greatly enhance sensitivity.

Future: Deep Core

To improve low E event efficiency



side view



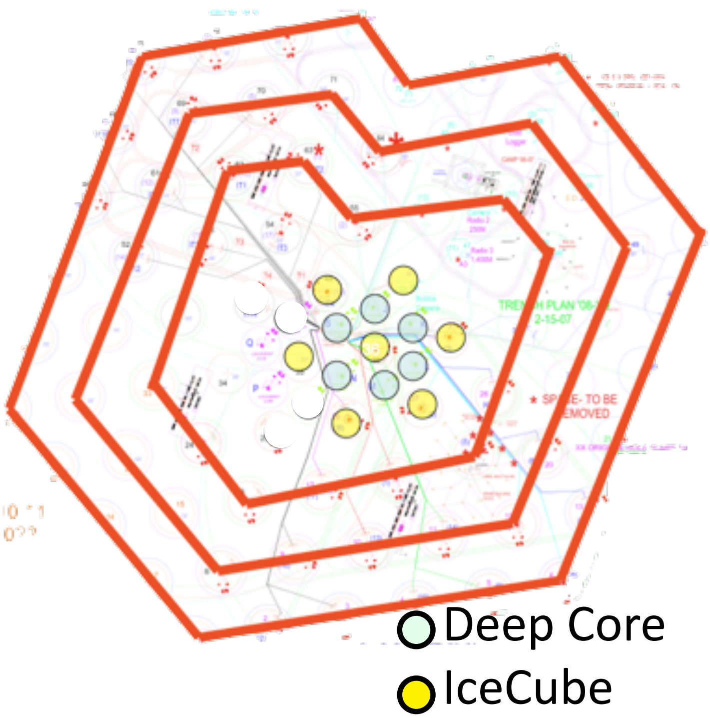
top view

Veto downgoing muons with IceCube

Rejection rate

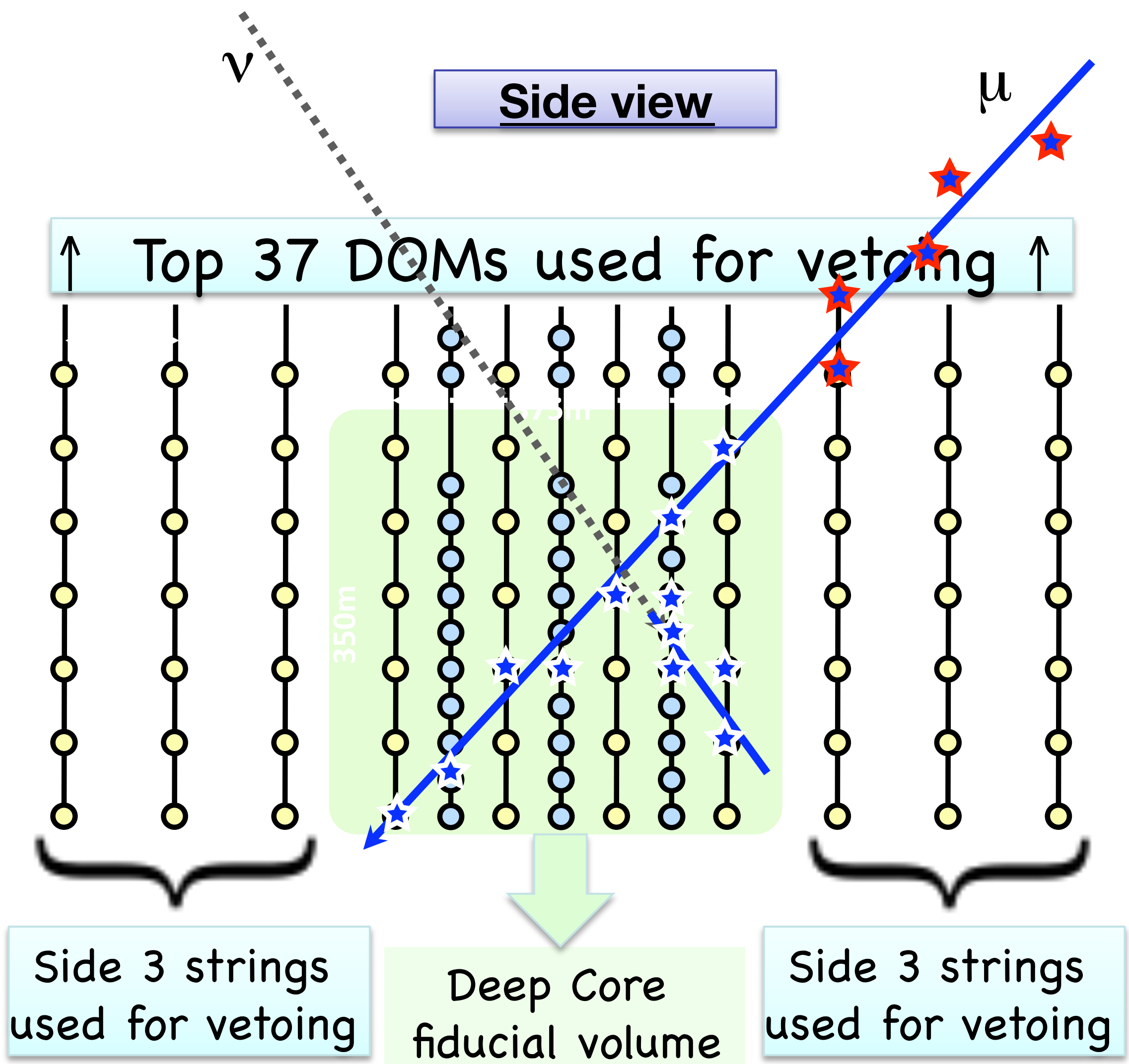
$$\phi(\mu)/\phi(\nu_{\text{atm}}) \simeq 10^6$$

Top view



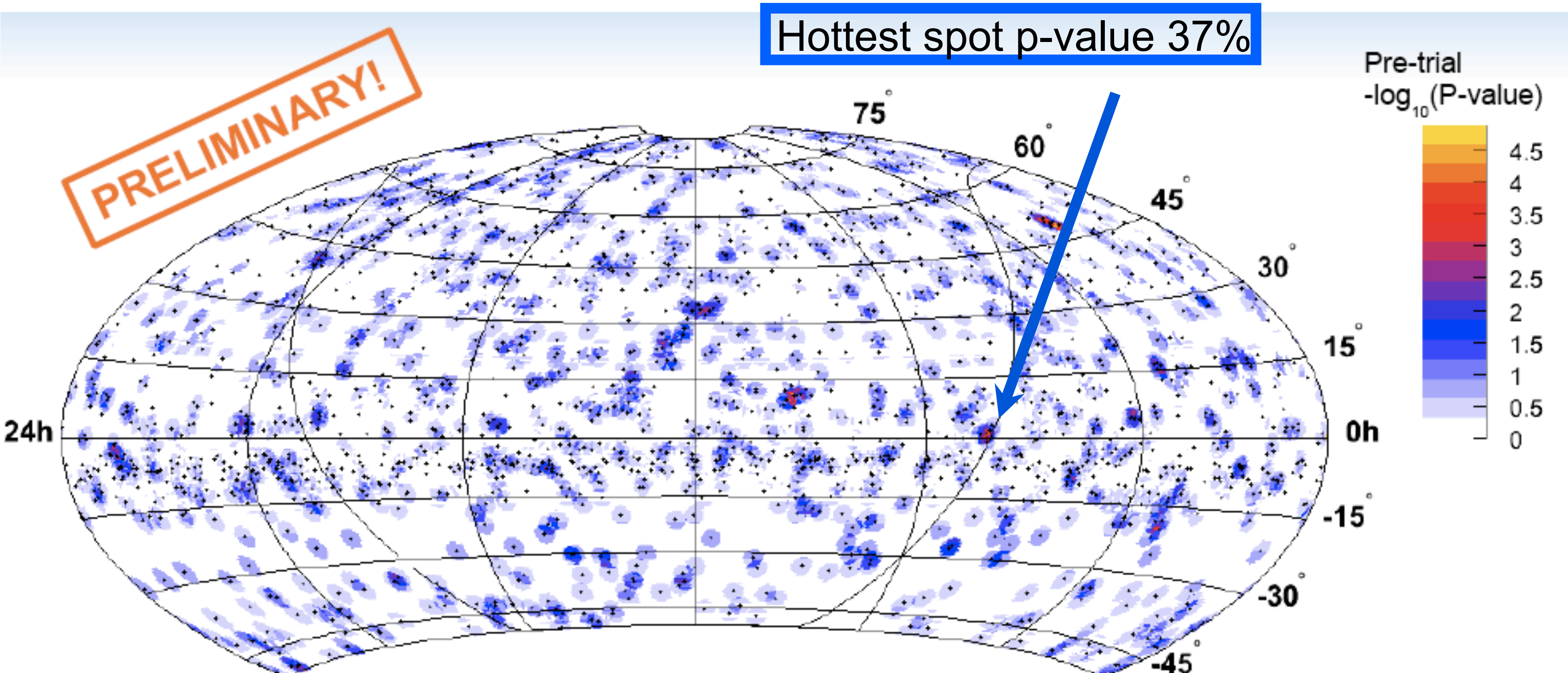
375 m thick active veto:
3 full IceCube string
layers surround Deep Core

veto allows searches above horizon!



Pointsource search – all sky at high energies

Apply energy cut o(100 to 1000TeV) in downgoing hemisphere as needed
To reject the muon background.

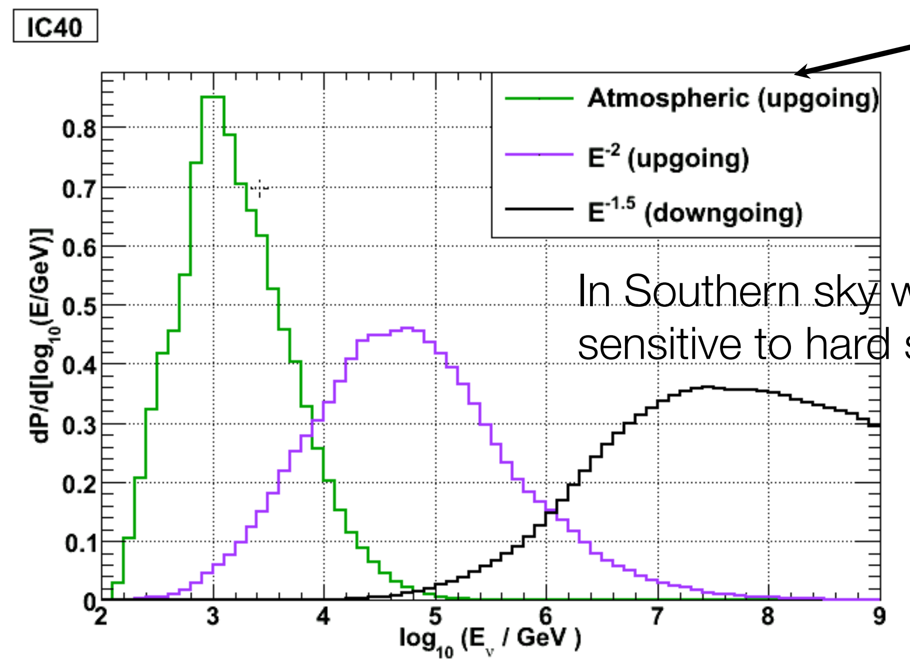


R. Lauer et al., Heidelberg Workshop, Jan09

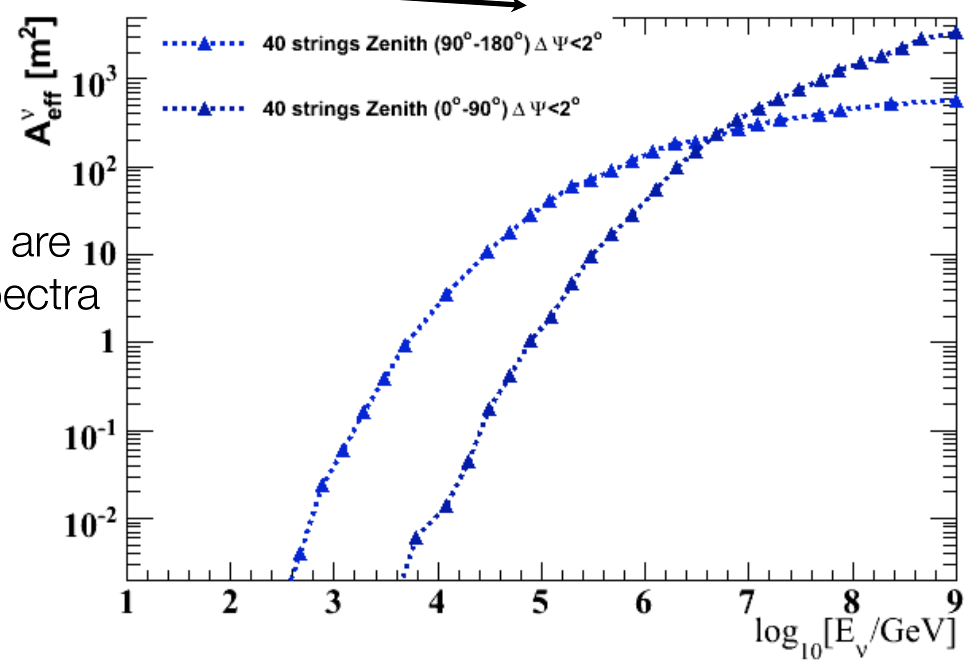
40 string - point-source analysis

In Northern sky we are sensitive to E^{-2} spectra

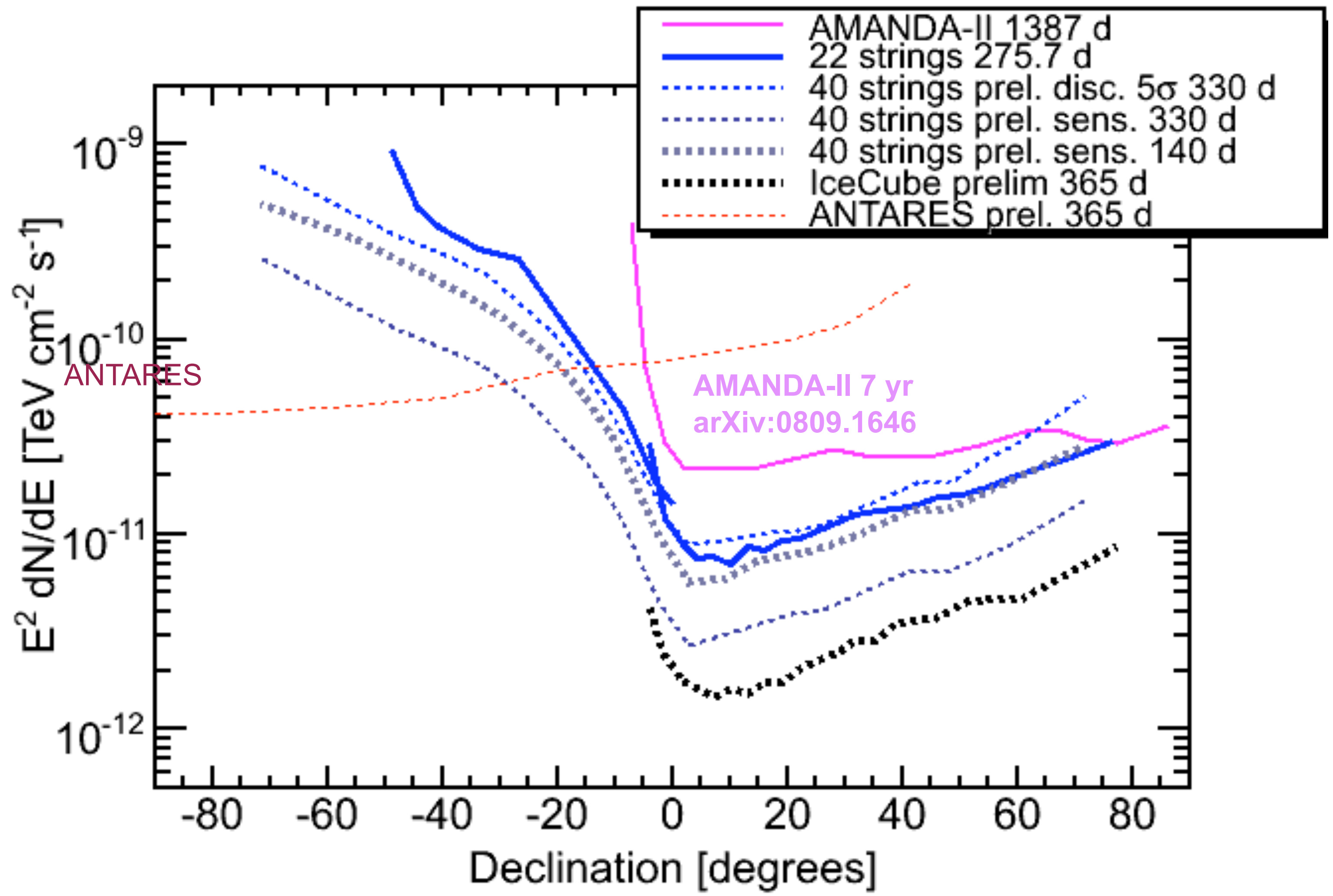
$$N_\mu = \int A^{\nu}_{eff}(E_\nu, \theta_\nu, \phi_\nu) \frac{d\Phi_\nu}{dE_\nu d\Omega_\nu} dE_\nu d\Omega_\nu$$



In Southern sky we are sensitive to hard spectra

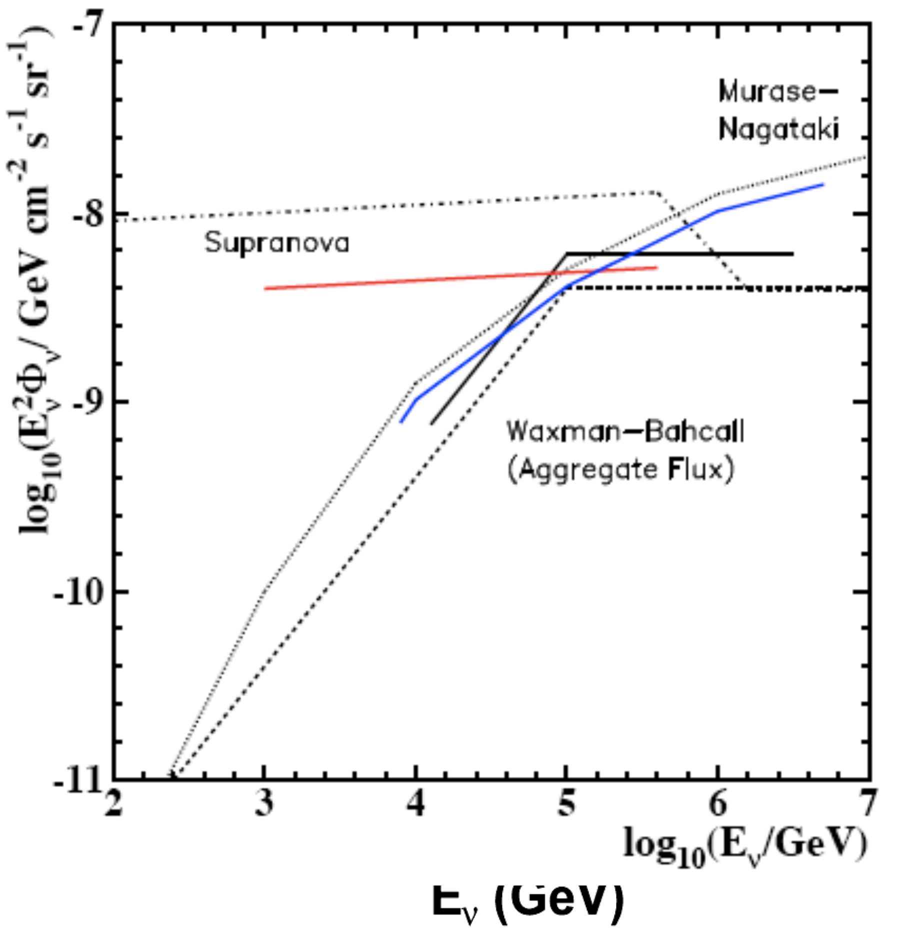


What fluxes accessible by experiments?



Slide by T. Montaruli

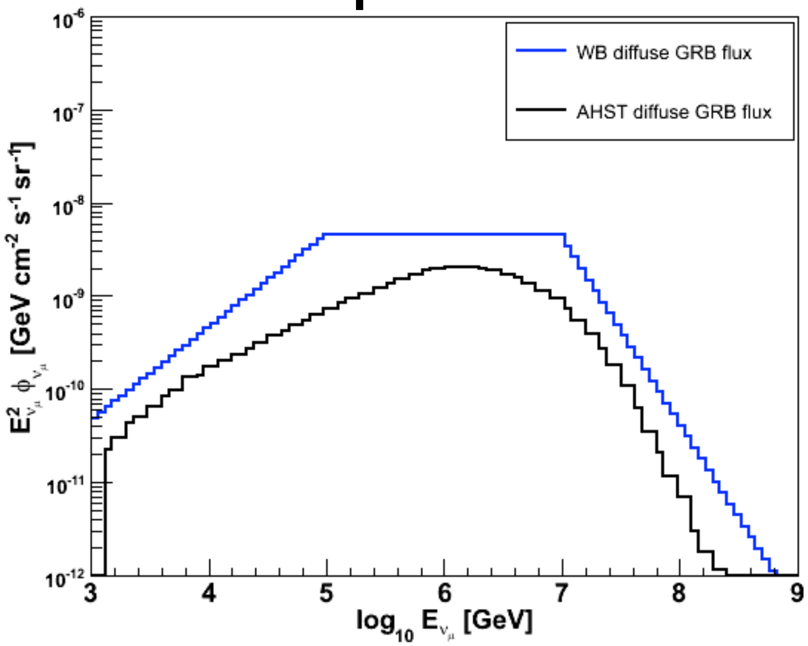
GRBs



- Look for spatial and temporal coincidences with satellite observations-low background search
- New satellites, Swift, GLAST, improve observations
- cascade searches (triggered and rolling) yield flux limits that are 1-2 orders of magnitude higher

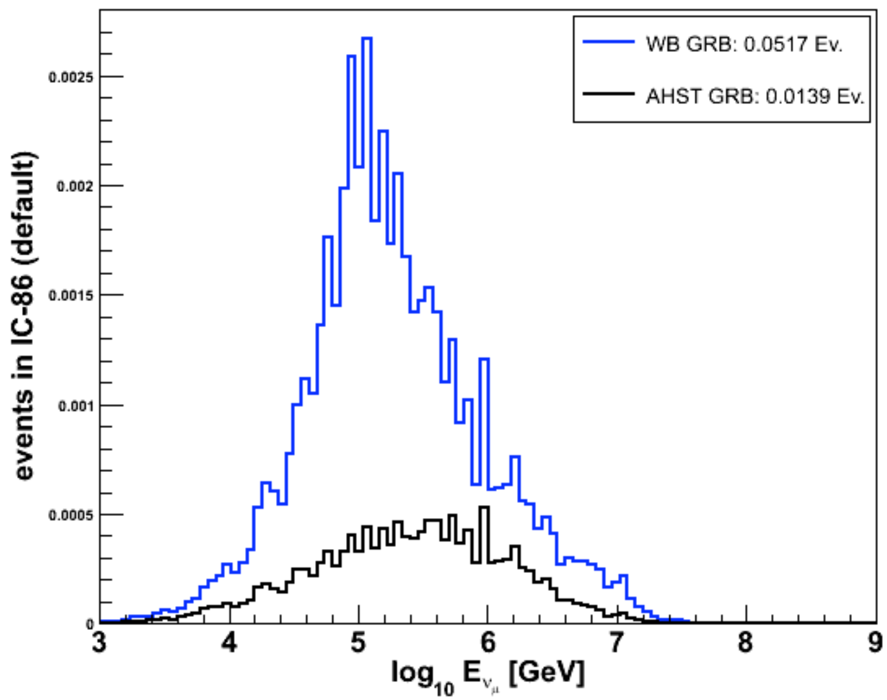
400 bursts

GRB fluxes,
Comparison of WBs and AHST spectra



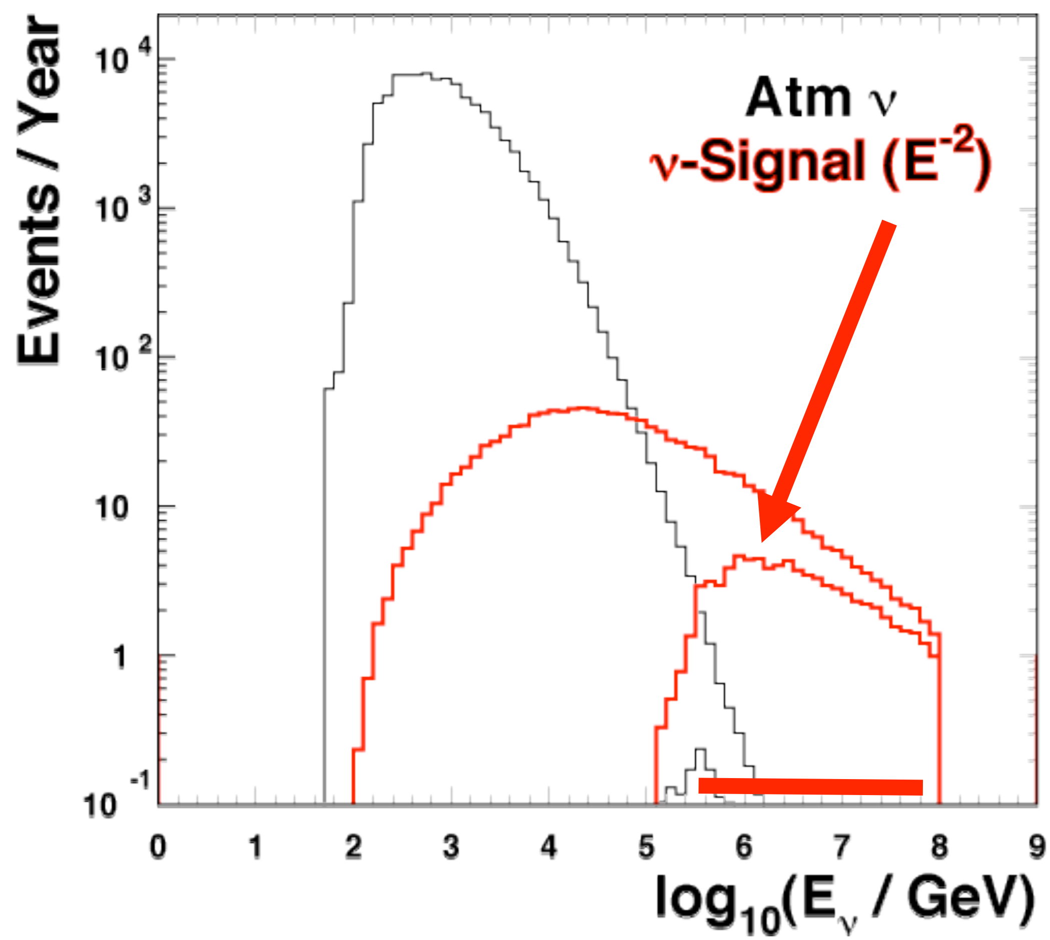
IceCube 86
WB: 10.6 total evts / year
(170 bursts per year)

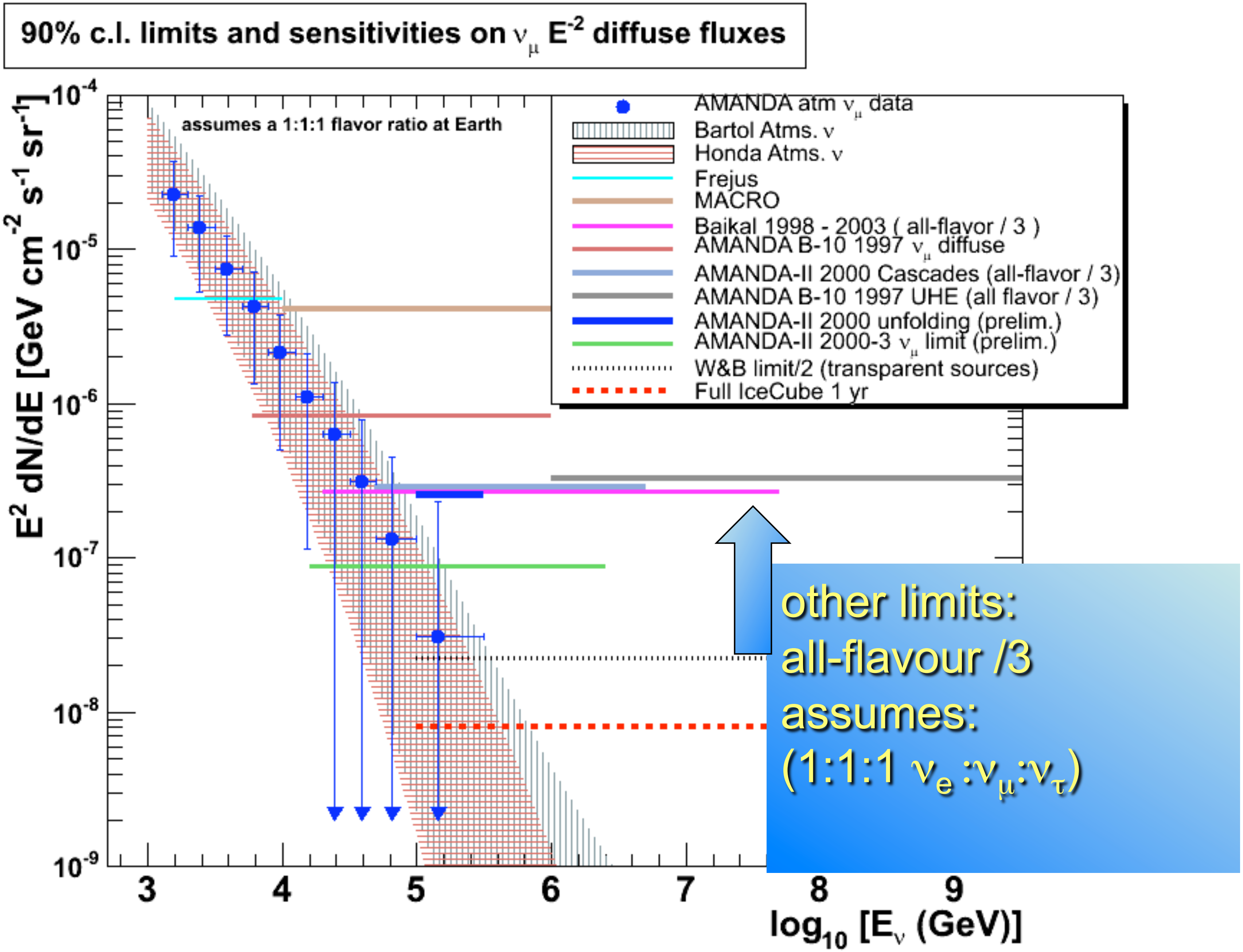
Significance of discovery
Is dominated by the high
energy events.
Median energy of events 100
to 300 TeV, may be higher.



Diffuse E^{-2} ν_μ-spectrum peaks at 1 PeV (after atm. Background rejection)

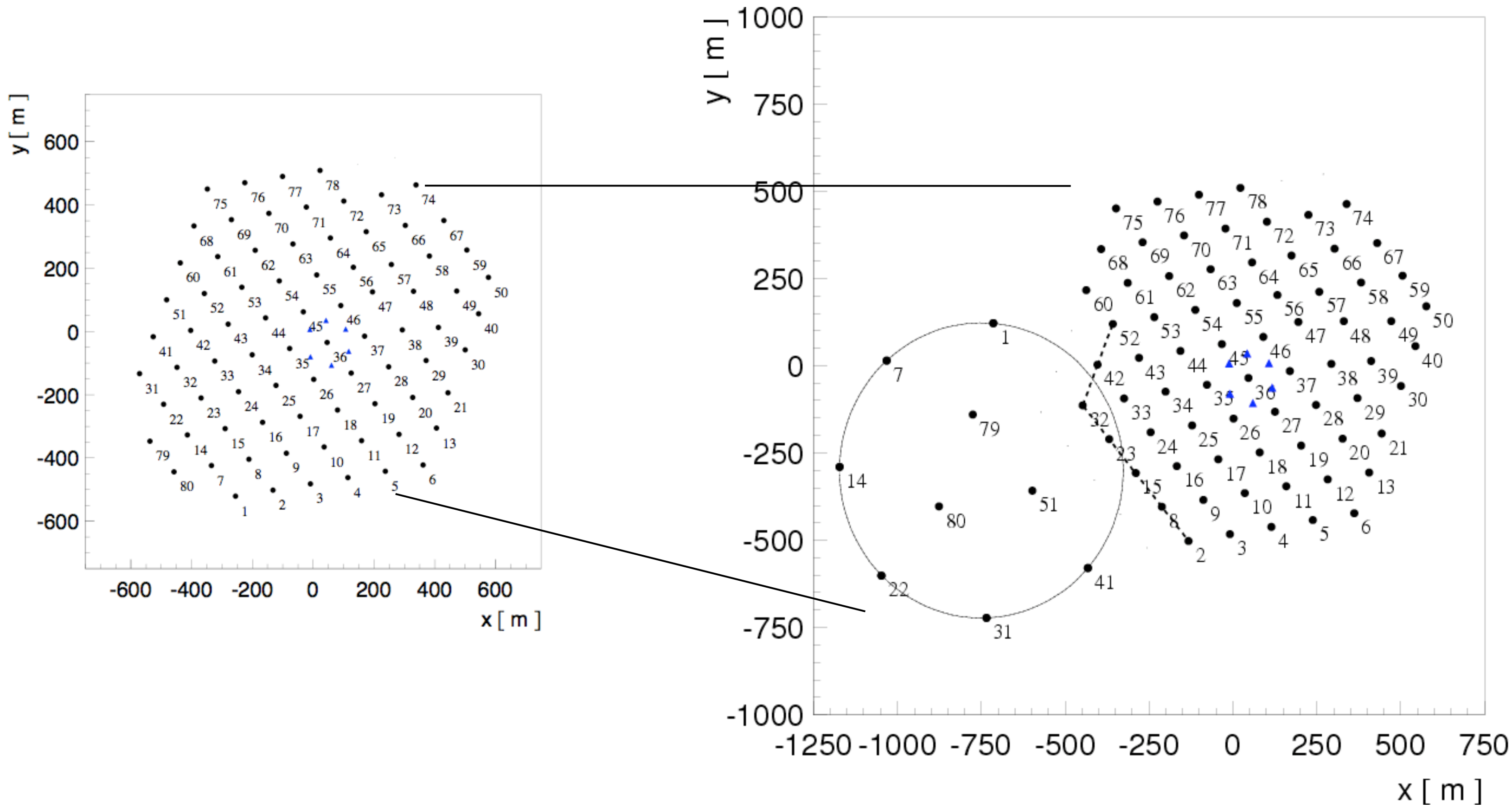
- Neutrino event energy spectrum after energy cut for a 3 year diffuse analysis.
- Signal events peak at ~1PeV
- Optimize final detector configuration for higher energy range, to maximize sensitivity of IceCube.





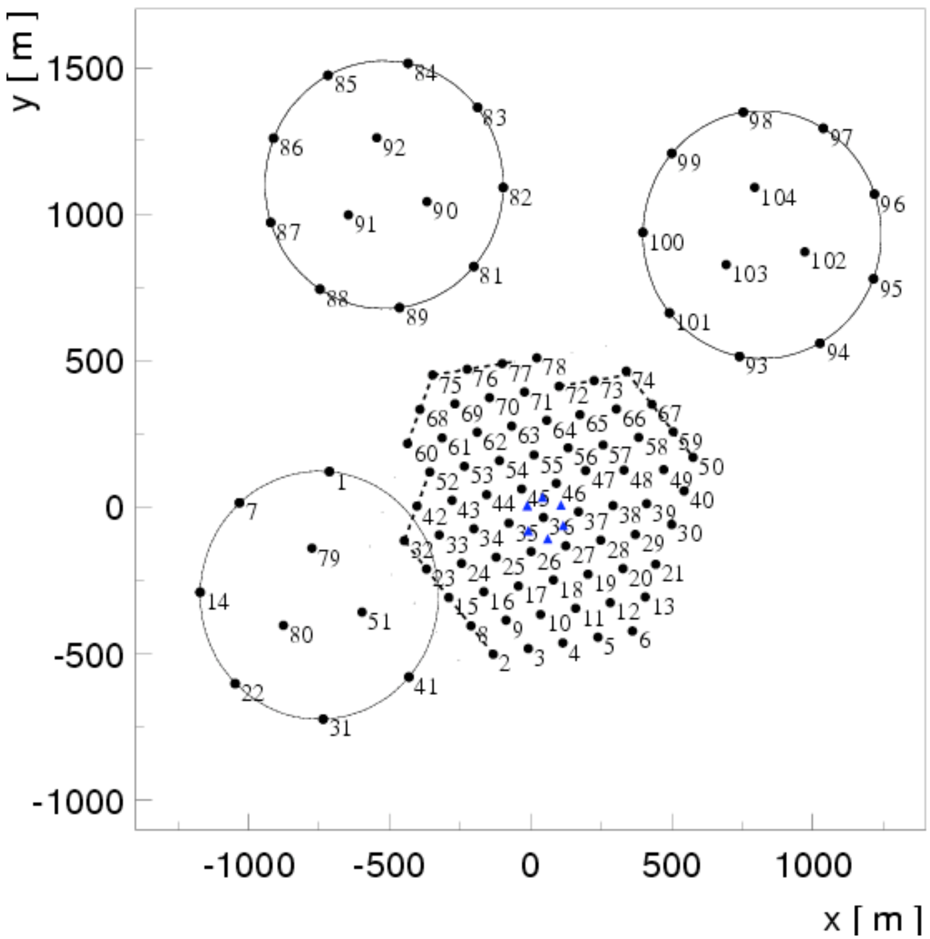
90% c.l. limits and sensitivities on ν_μ E^{-2} diffuse fluxes
assumes a 1:1:1 flavor ratio at Earth
E^2 dN/dE [GeV cm^{-2} s^{-1} sr^{-1}]
$\log_{10}$ [E_ν (GeV)]
AMANDA atm ν_μ data
Bartol Atms. ν
Honda Atms. ν
Frejus
MACRO
Baikal 1998 - 2003 (all-flavor / 3)
AMANDA B-10 1997 ν_μ diffuse
AMANDA-II 2000 Cascades (all-flavor / 3)
AMANDA B-10 1997 UHE (all flavor / 3)
AMANDA-II 2000 unfolding (prelim.)
AMANDA-II 2000-3 ν_μ limit (prelim.)
W&B limit/2 (transparent sources)
Full IceCube 1 yr
other limits:
all-flavour /3
assumes:
(1:1:1 $\nu_e:\nu_\mu:\nu_\tau$)

Geometry of high energy optimized configuration



Drilling of 9 holes in the last season inside a circle with radius of 0.4 to 0.5 km is possible.

An large optical extension?–
Scenario for 110 strings



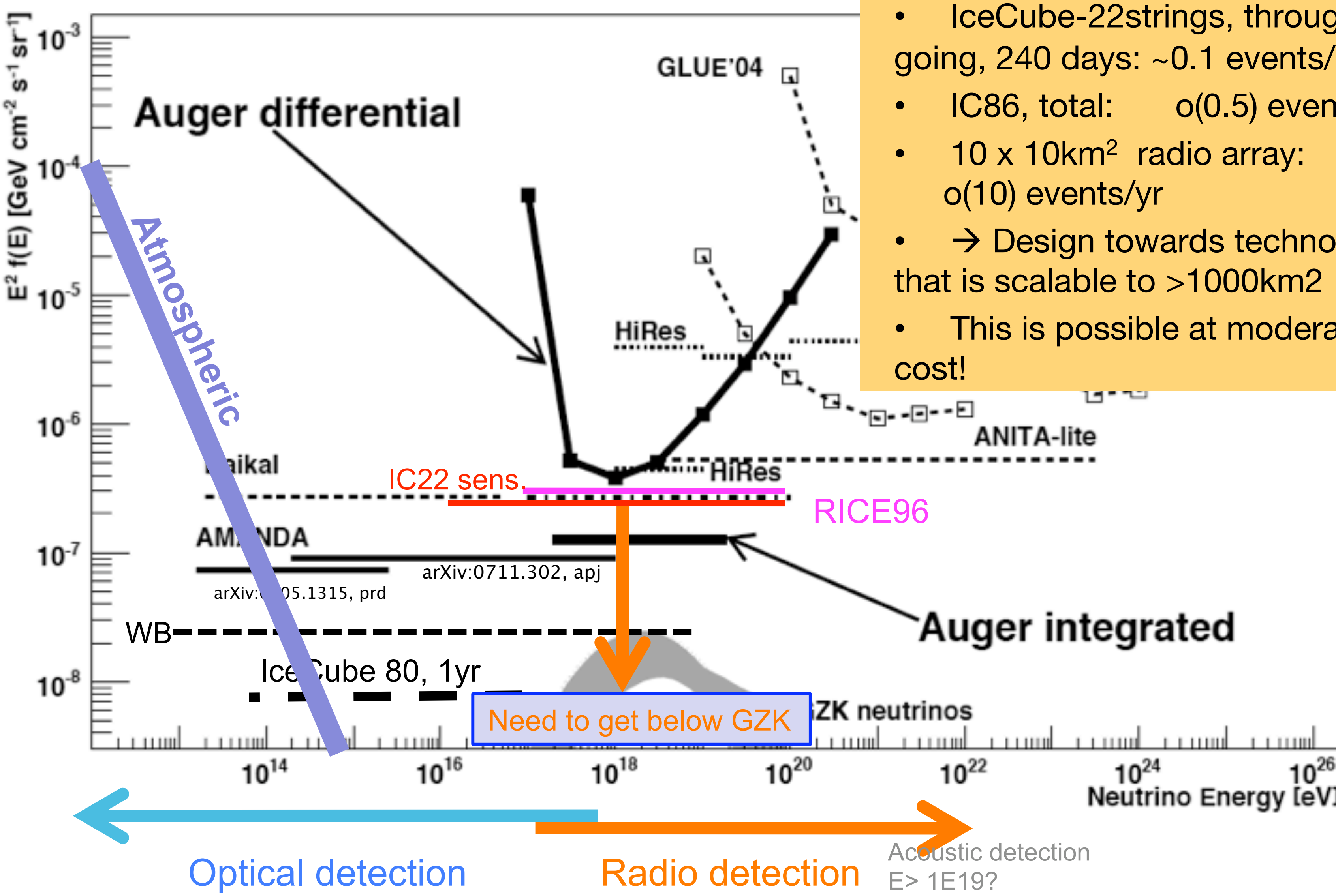
Outriggers fully efficient at ~1 PeV.

Double size of IceCube for ~$20M?

Still hard work.

Can we gain a much larger factor?

Diffuse fluxes limits at higher energies



Event rates for

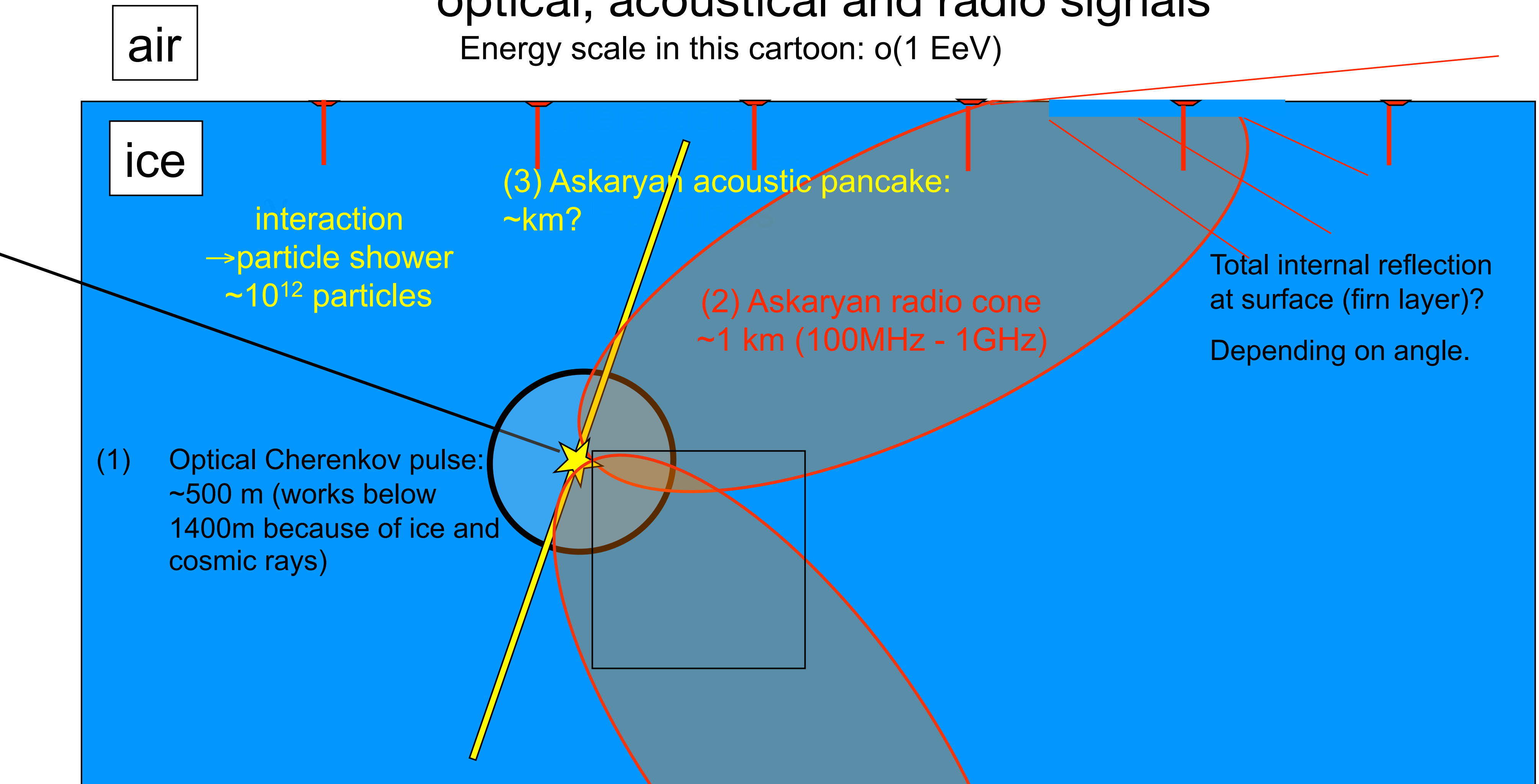
Flux: Engel, Seckel, Stanev, 2001)

(Factor of 10 higher still allowed by current limits, including IceCube)

- IceCube-22strings, through going, 240 days: ~0.1 events/yr
- IC86, total: o(0.5) event/yr
- 10 x 10km² radio array: o(10) events/yr
- → Design towards technology that is scalable to >1000km2
- This is possible at moderate cost!

Neutrino induced cascades produce 3 types signals: optical, acoustical and radio signals

Energy scale in this cartoon: o(1 EeV)



radio and acoustic waves travel farther than light in ice
They require less drilling as they can travel through bubbly ice and firn (radio)

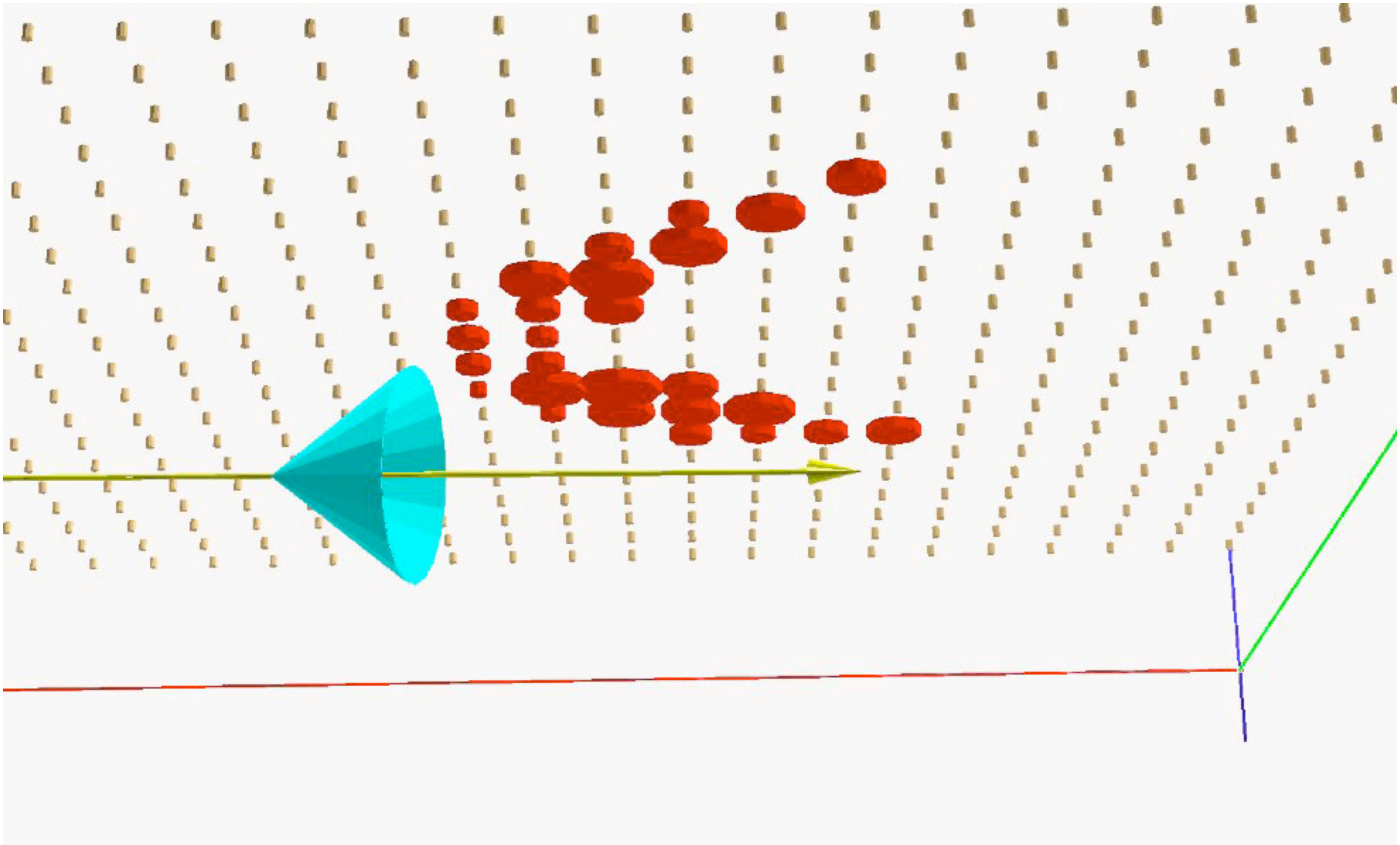
Radio detection of high energy showers

- Radio emission predicted by Askaryan
- Effect tested in SLAC experiment by members of ANITA collaboration

Two processes to distinguish

1. Geosynchrotron radiation of electrons and positrons in cosmic ray air showers in Earth magnetic field
2. Askaryan effect: Radio Cherenkov emission, net charge moving through dielectric medium at vacuum speed of light. Interesting frequency range: 50MHz to multi GHz.

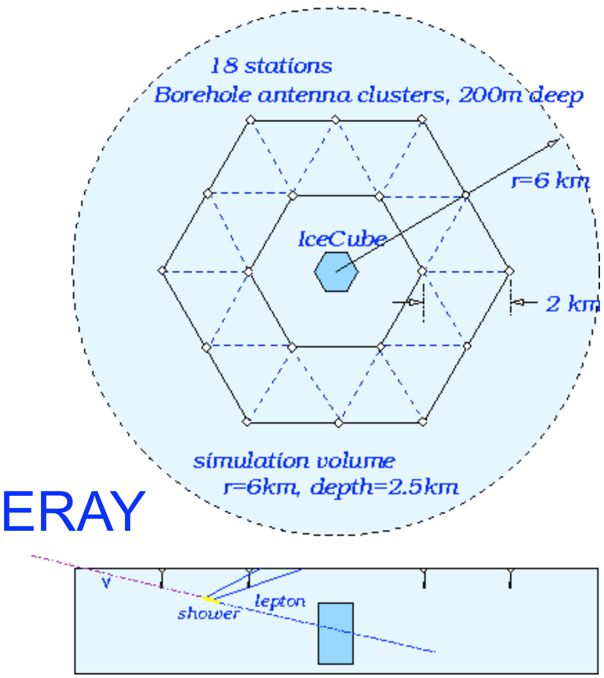
in-ice view of radio detection



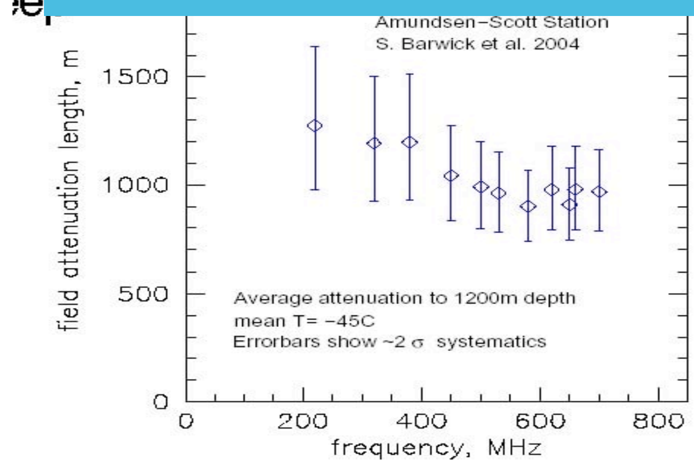
Future possibilities
UHE Radio Augmentation around IceCube
acoustic instrumentation

- GZK neutrinos ($10^{17\text{-}19.5}$ eV), at lowest possible cost: Fluxes may be very low, plan for few events/ 100km3/yr
- Must develop technology to scale beyond o(1000)km^3
- Hybrid events with IceCube
  - Primary vertex calorimetry in radio, HE muon or tau secondary in IceCube
- Understand medium and noise conditions

ICERAY

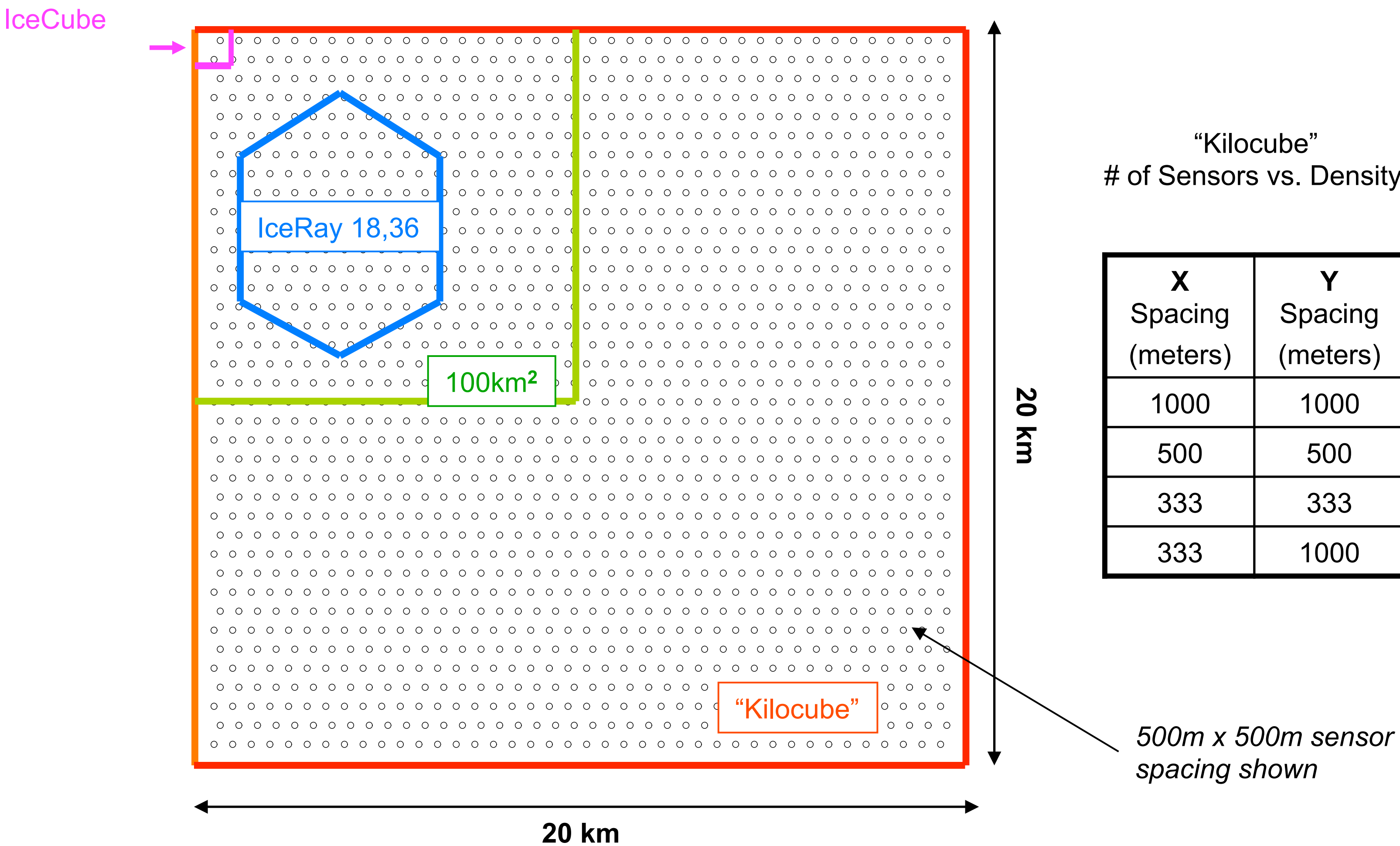


>Km scale attenuation length
In South Pole ice



Barwick et al., 2004

Some Detector Footprints
- all small compared to Auger

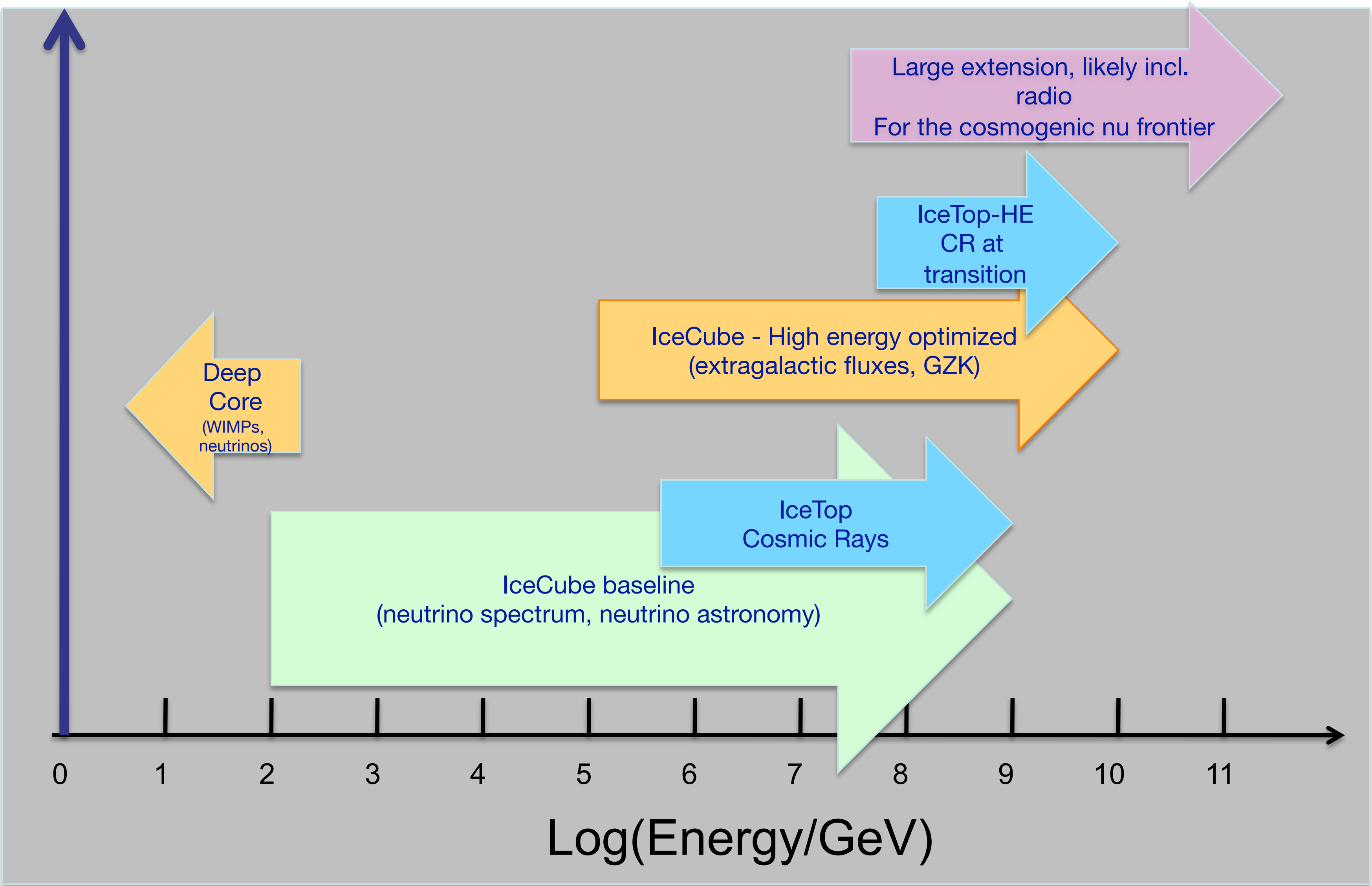


"Kilocube"
# of Sensors vs. Density:

X Spacing (meters)	**Y** Spacing (meters)	**Total # of Sensors**
1000	1000	**400**
500	500	**1600**
333	333	**3600**
333	1000	**1200**

Cost: between $10M and $30M

IceCube - Enhancement options



Not mentioned in this talk

- All things IceCube can do with 10s of billions of >TeV downgoing muons
  - Anisotropy analysis in the Southern sky (→ ICRC)
  - Atmospheric pressure/temperature and cosmic ray correlations
  - Gamma astronomy (bursts)
- Cosmic ray physics analysis (spctrum, composition to 1E18)
- Supernova detection
- MWL activities

Conclusions

- Huge progress in neutrino astronomy.
- AMANDA has set the most constraining limits for astrophysical neutrinos. It has done well – and been turned off last month.

The 5th IceCube construction season:

- **59 strings in operation!**
- **Construction on budget and on schedule**
- **86 strings in 2011. Rapid increase in discovery potential in the next years.**

First results from first science run with 22 strings. Will present 40 string data at ICRC.

IceCube started neutrino astronomy in 4 π.

Physicists in IceCube and ANITA collaborations are working on R&D for a large GZK neutrino detector.

Albrecht Karle, UW-Madison

Albrecht Karle, UW-Madison

Al Shepard, Apollo 14