PARTICLE PHYSICS WITH HIGH ENERGY NEUTRINO TELESCOPES

Kara Hoffman
University of Maryland
IceCube

NEUTRINO TELESCOPES

BAIKAL

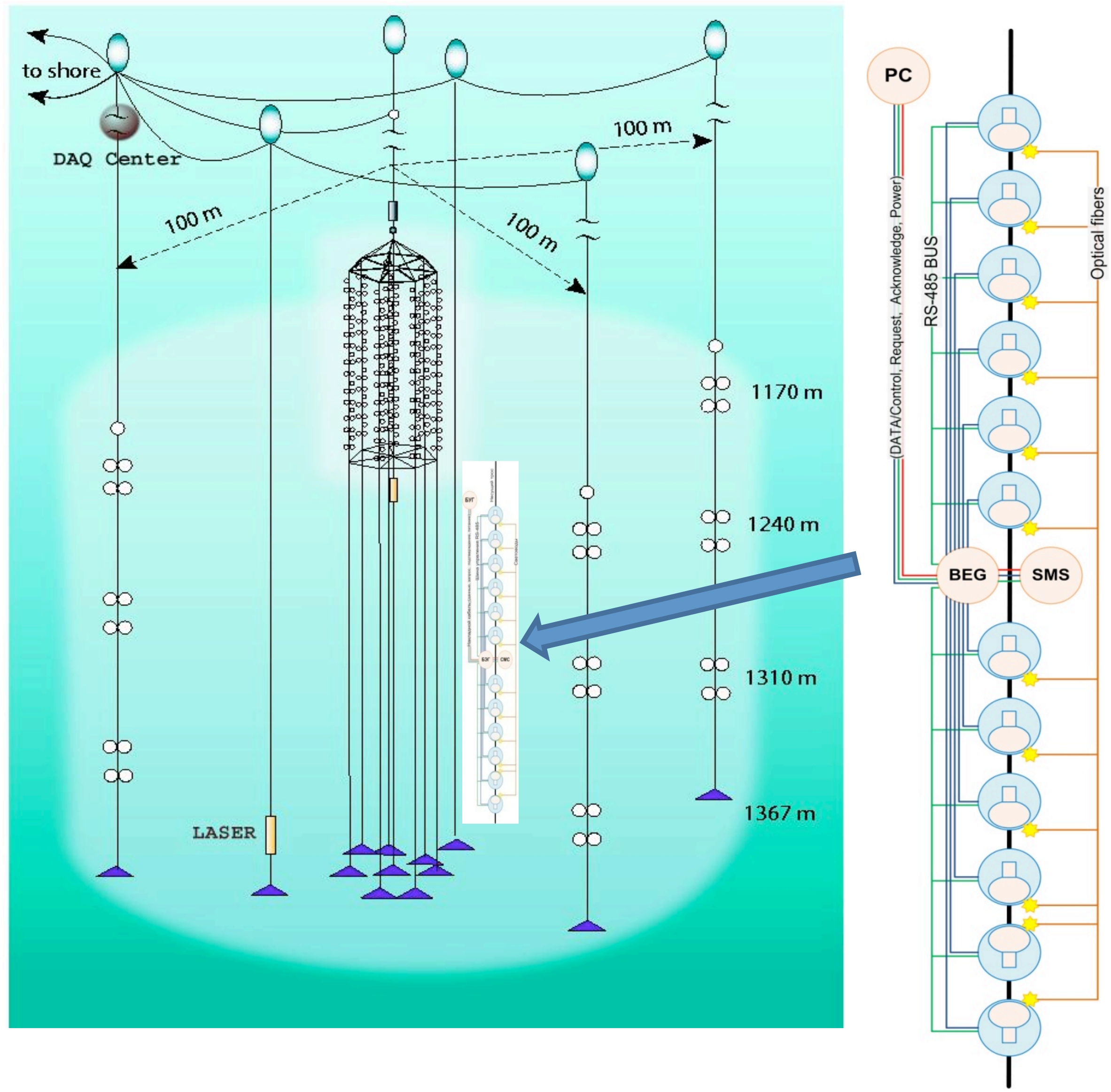
- **NT200 array:**
  - 192 Optical Modules
  - 8 Strings
  - 6.5 m between Modules
  - 20 m between strings
- **NT+ array:**
  - 36 Optical Modules
  - 3 distant Strings
- **New technology string:**
  - 12 Optical Modules
  - 10 m between Modules

Gigaton Volume upgrade:

12 clusters with 8 strings each

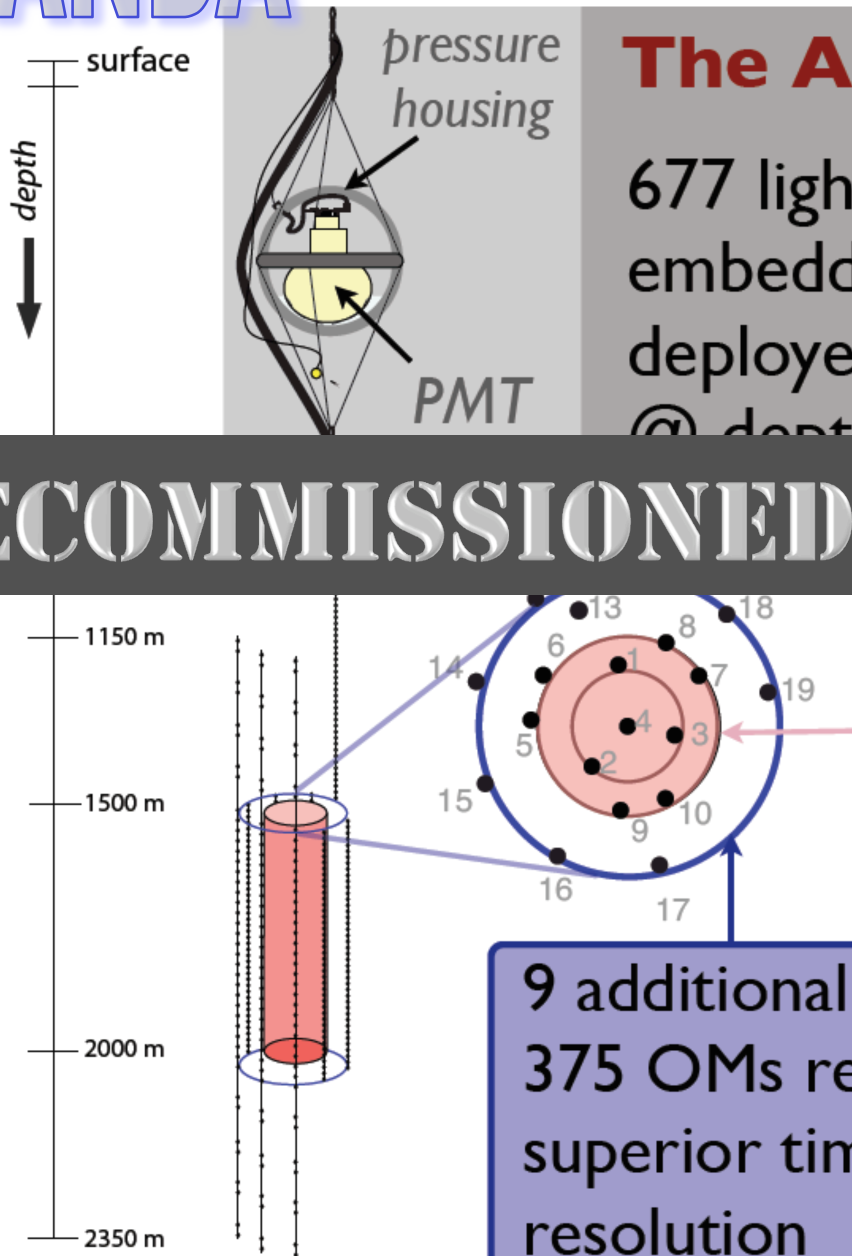
22-24 optical modules per string

2100-2300 modules total



AMANDA

the Antarctic Muon and Neutrino Array



The AMANDA-II Detector

677 light sensitive Optical Modules embedded in Antarctic ice sheet deployed on 19 "strings"
@ depths ~1500-2000m

DECOMMISSIONED MAY 18, 2009

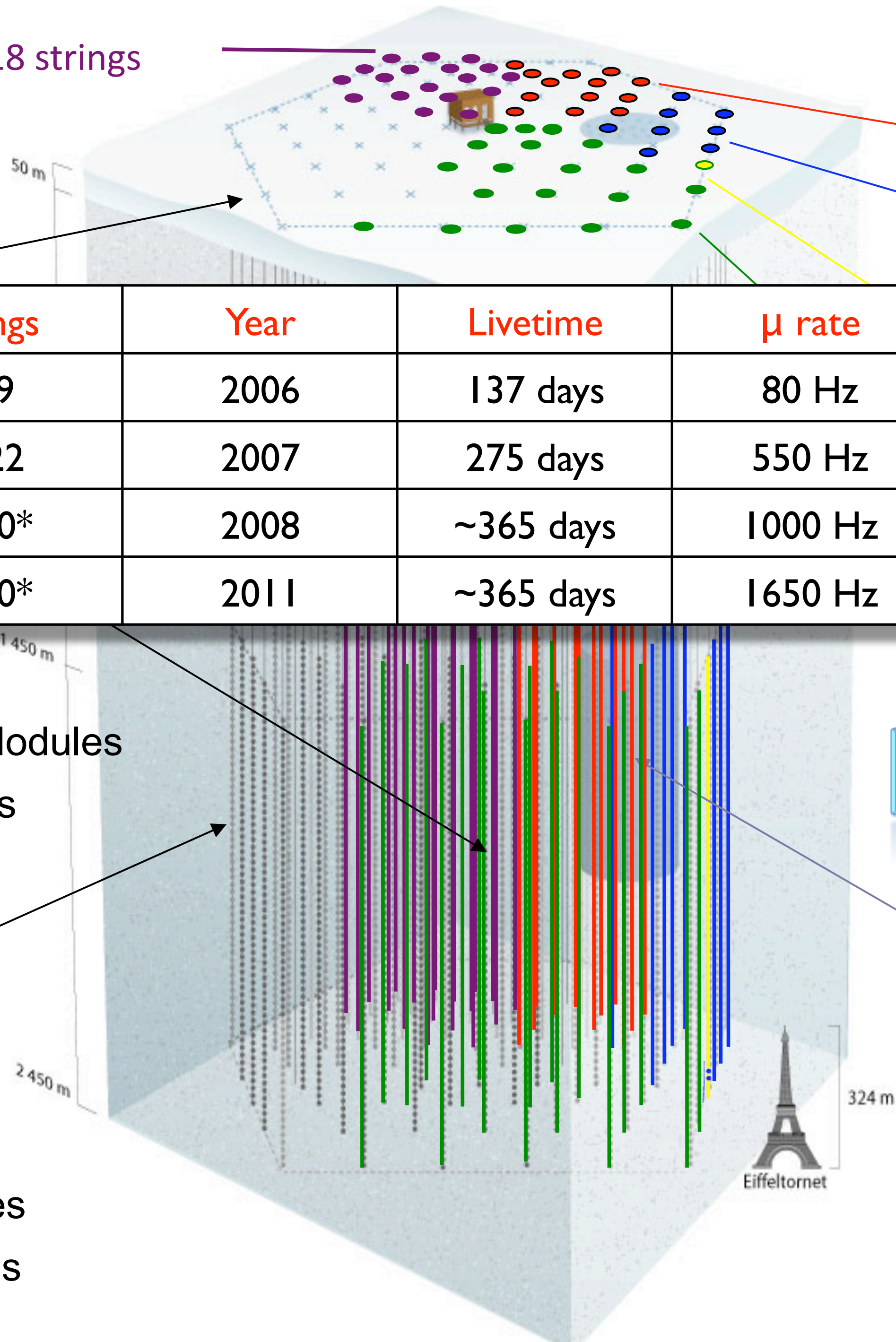
"AMANDA-B10" (10 strings)
302 OMs read out via *coaxial* or *twisted-pair electrical* cables

9 additional strings
375 OMs read out via *optical fibers*
superior timing- and double pulse resolution

2007-2008: 18 strings

2006-2007: 13 strings

2005-2006: 8 strings



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

ring

rings

ings

operating

DeepC

6 additional strings ,

60 Optical Modules

7 or 10 m between Modules

72 m between Strings

ICECUBE

AMANDA

19 Strings

677 Modules

InIce

70-80 Strings ,

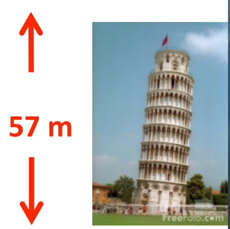
60 Optical Modules

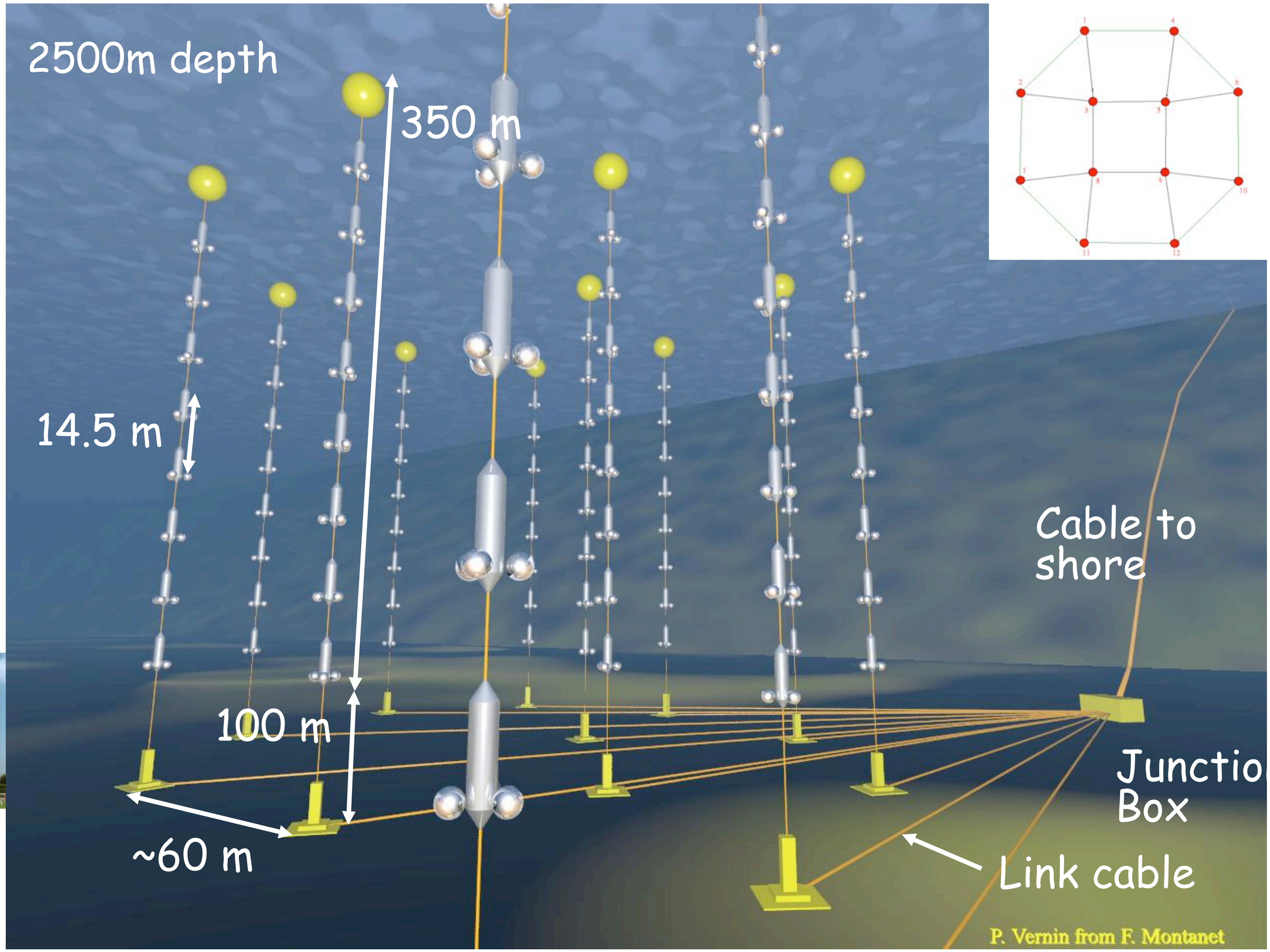
17 m between Modules

125 m between Strings

ANTARES

Northern Hemisphere- Mediterranean Sea

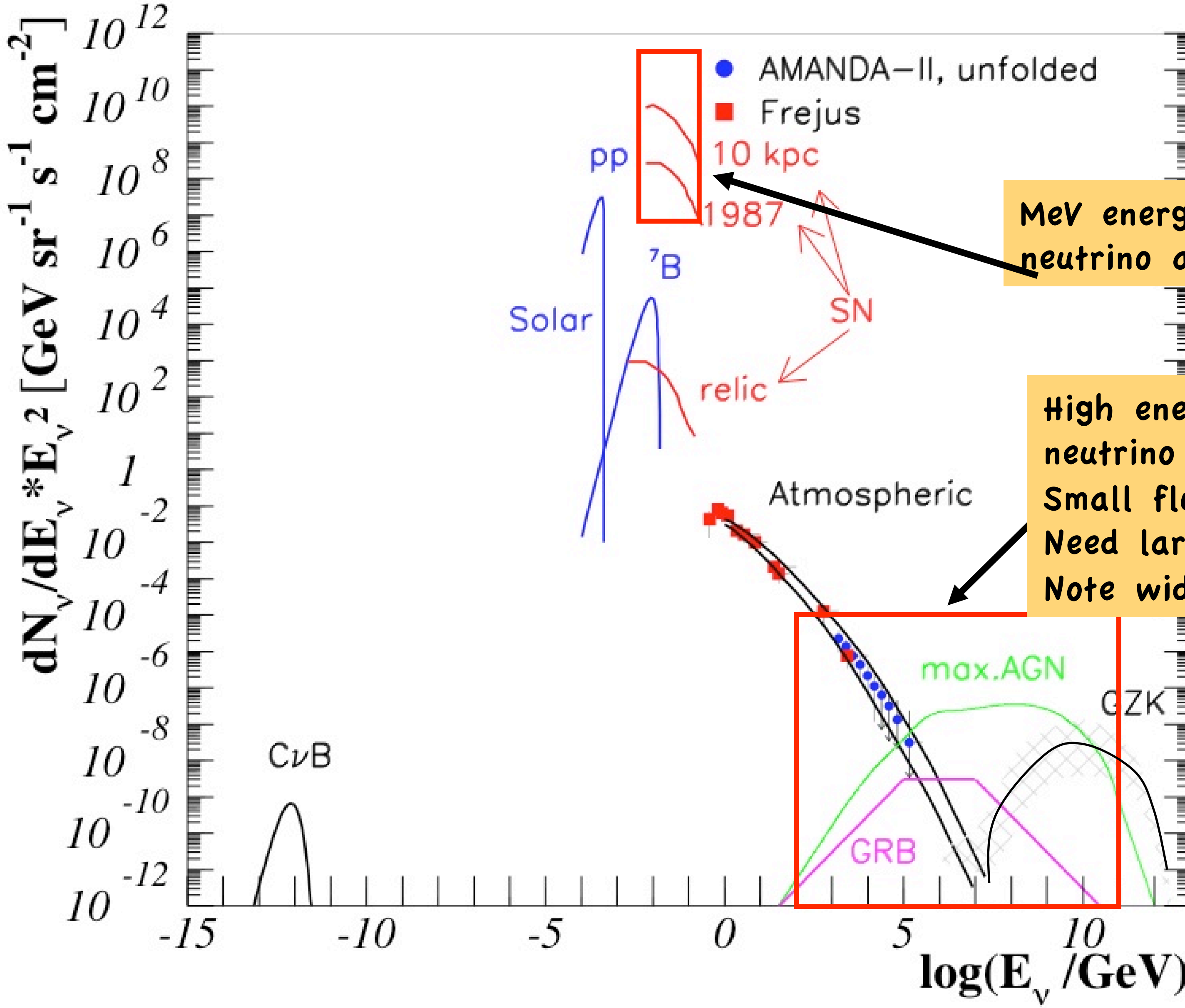




Summary

	location	phototubes	instrumented area (km^2)	date of operation
Lake Baikal	Siberia			
NT36,72,96		36,72,96		1993
NT200		192	.002	1998
AMANDA	South Pole			
AMANDA B-10		302	.01	1997
AMANDA II		677	.03	2000
IceCube	South Pole			
IC-9		540	.1	2006
IC-22		1320	.25	2007
IC-40		2400	.5	2008
IC-80		4800	1	2011
ANTARES	Mediterranean	900	.03	2008
Nestor	Mediterranean			R&D
Nemo	Mediterranean			R&D
KM3Net	Mediterranean		1	Design Phase

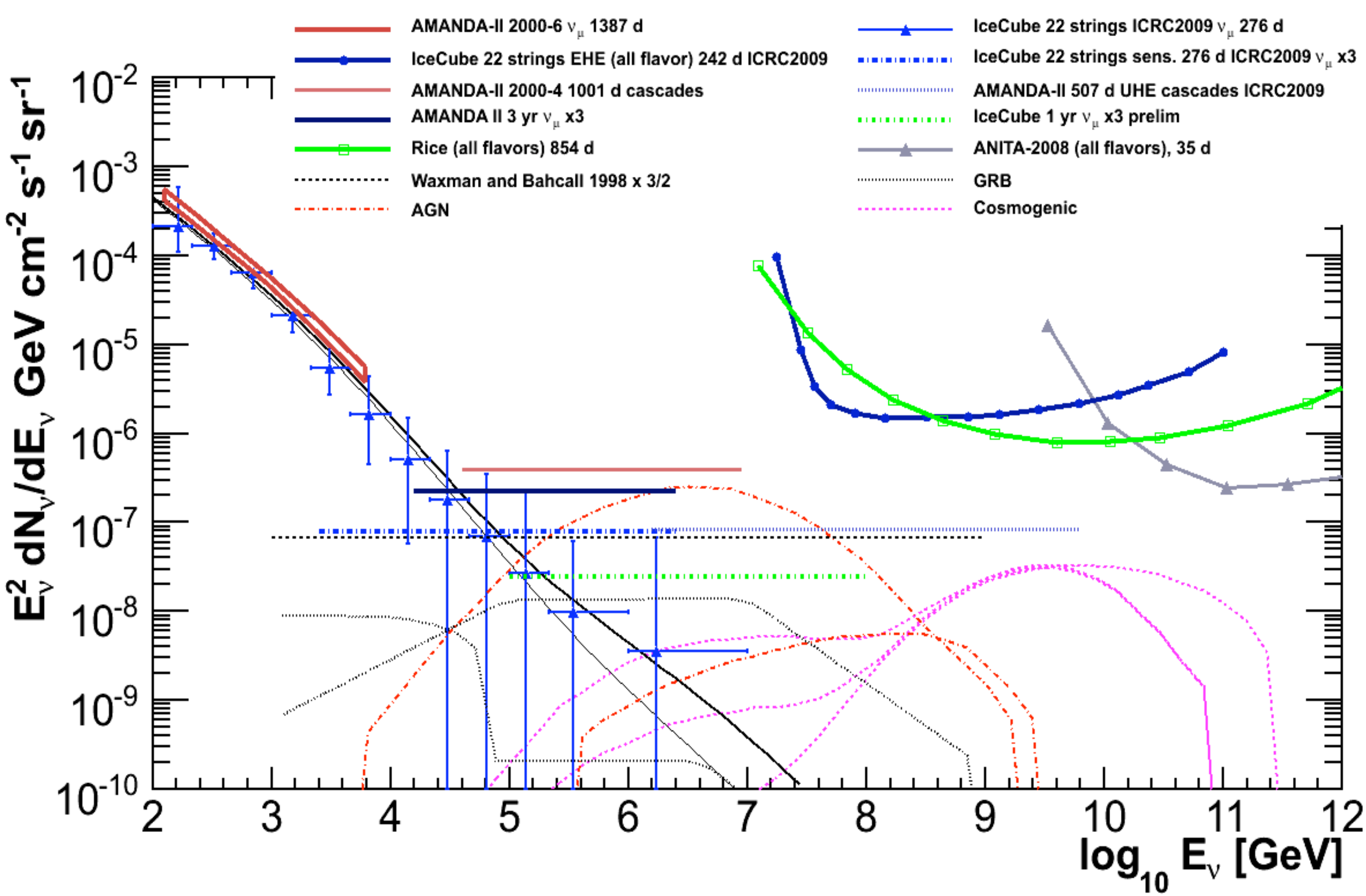
Astrophysical ν's: Sources, energies and fluxes



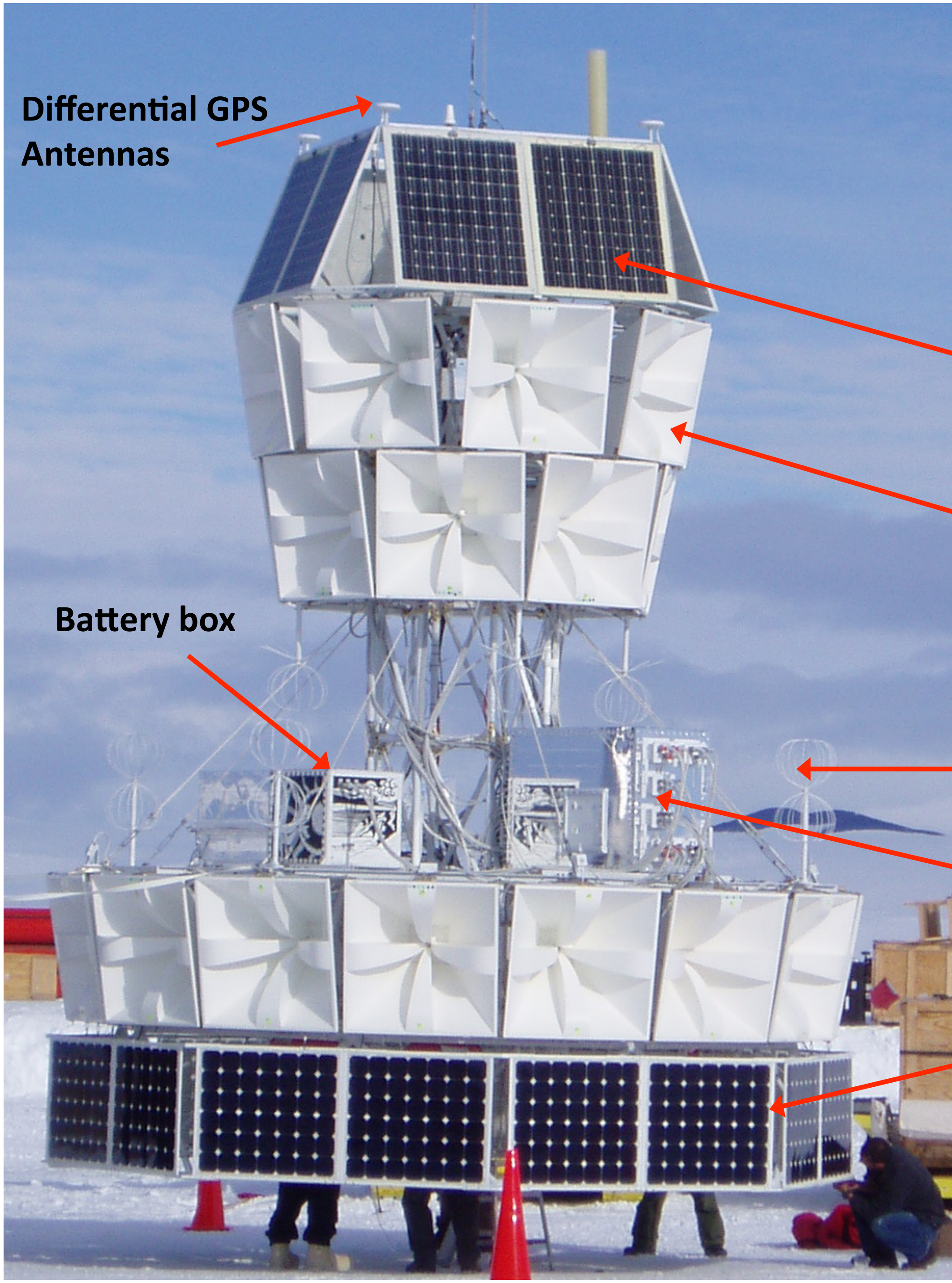
MeV energy neutrino astrophysics

High energy neutrino astronomy:
Small fluxes,
Need large detectors,
Note wide energy range

High Energy ν "Telescopes"



ANITA



Solar cells for NASA equipment

32 Quad-ridge horn antennas
- 200 MHz to 1200 MHz
- 10 degree downward angle

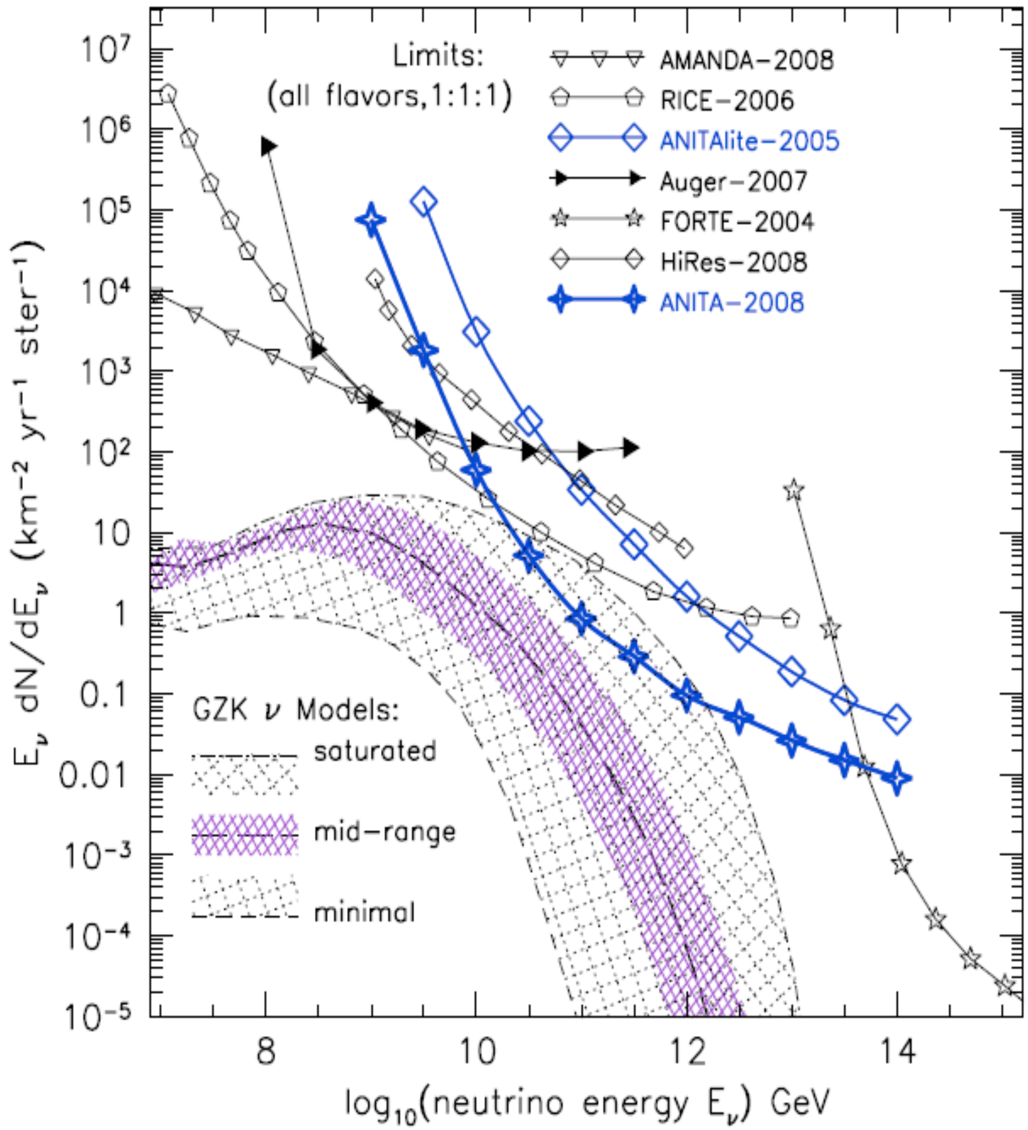
8 low gain antennas to monitor payload-generated noise

ANITA electronics box

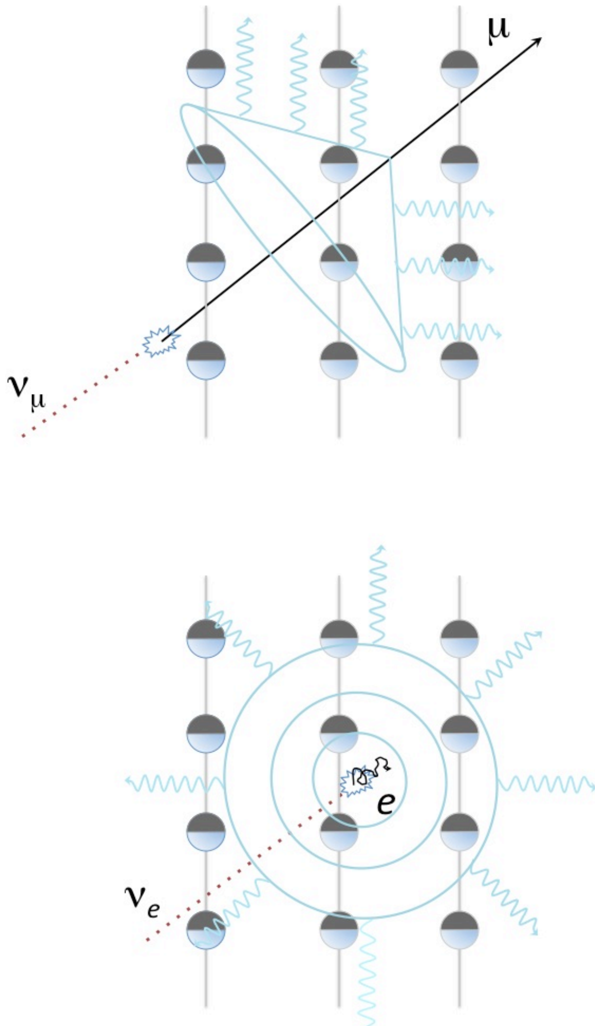
Solar panels for science mission

“instrument paper”: (50 pp!)
arXiv:0812.1920 [astro-ph]

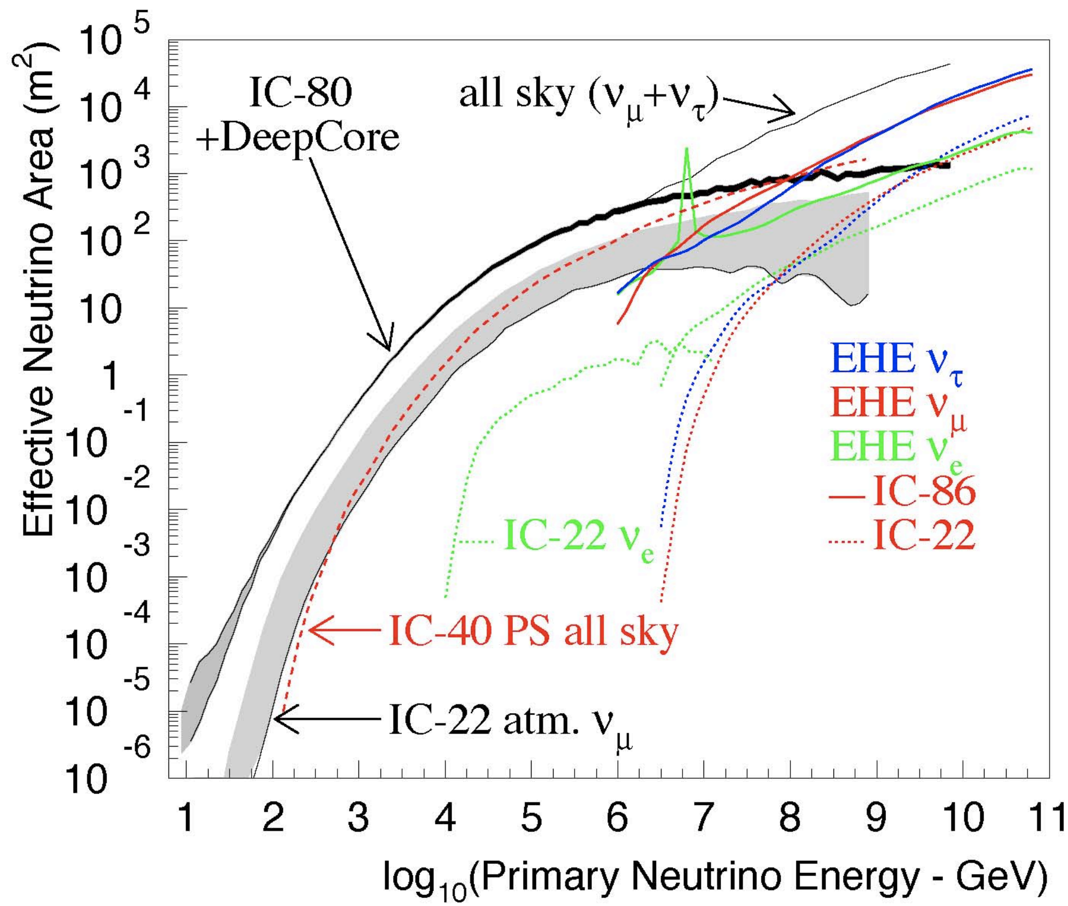
Really High Energy ν Telescopes



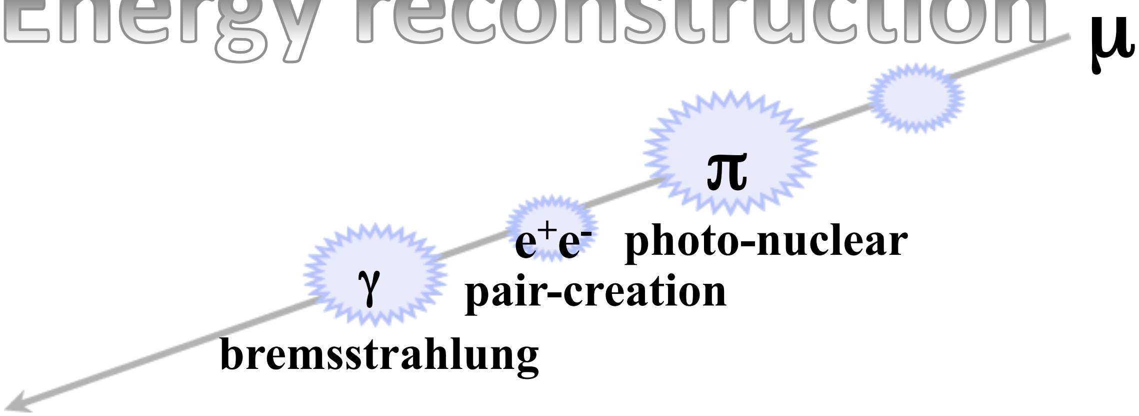
Neutrino reconstruction



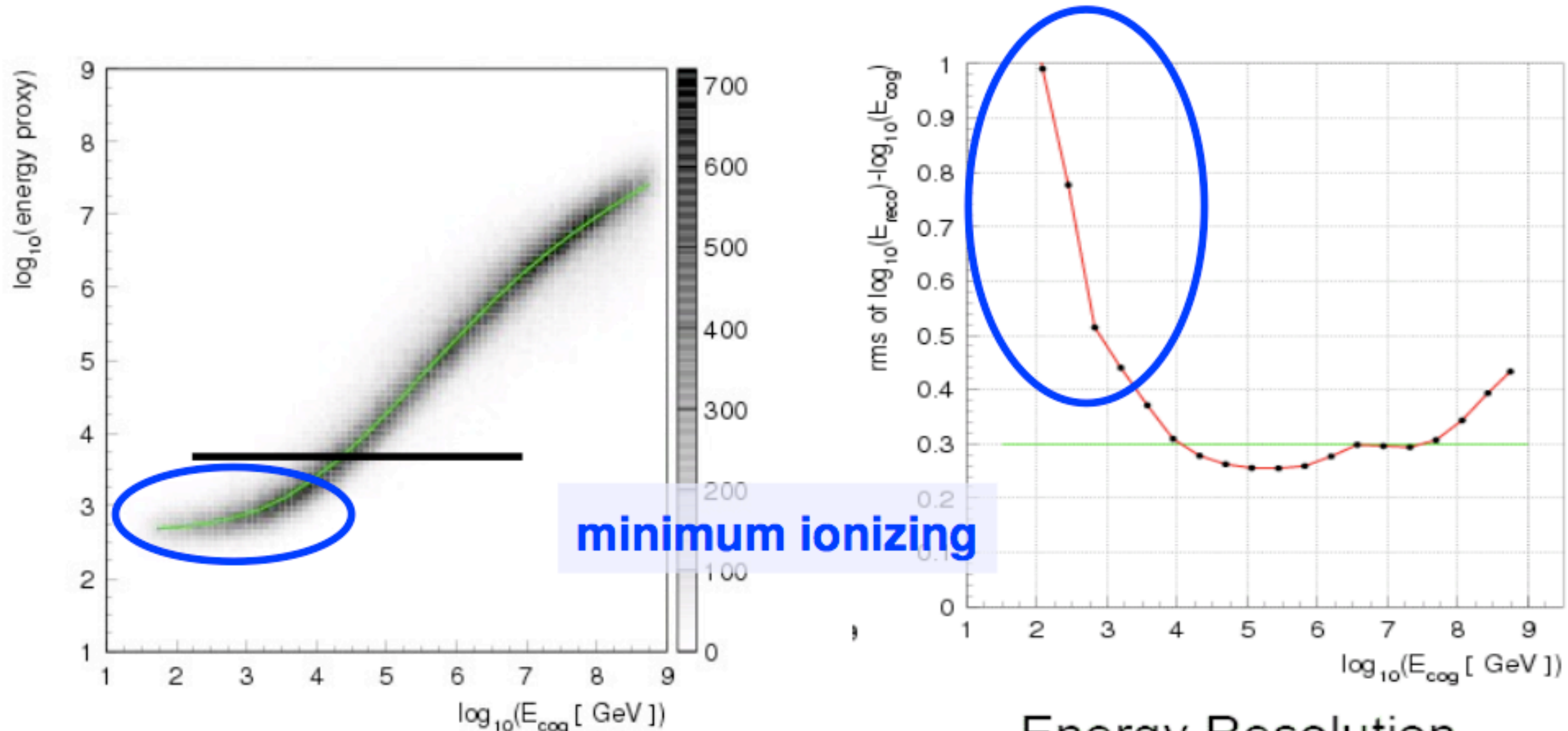
IceCube



Energy reconstruction



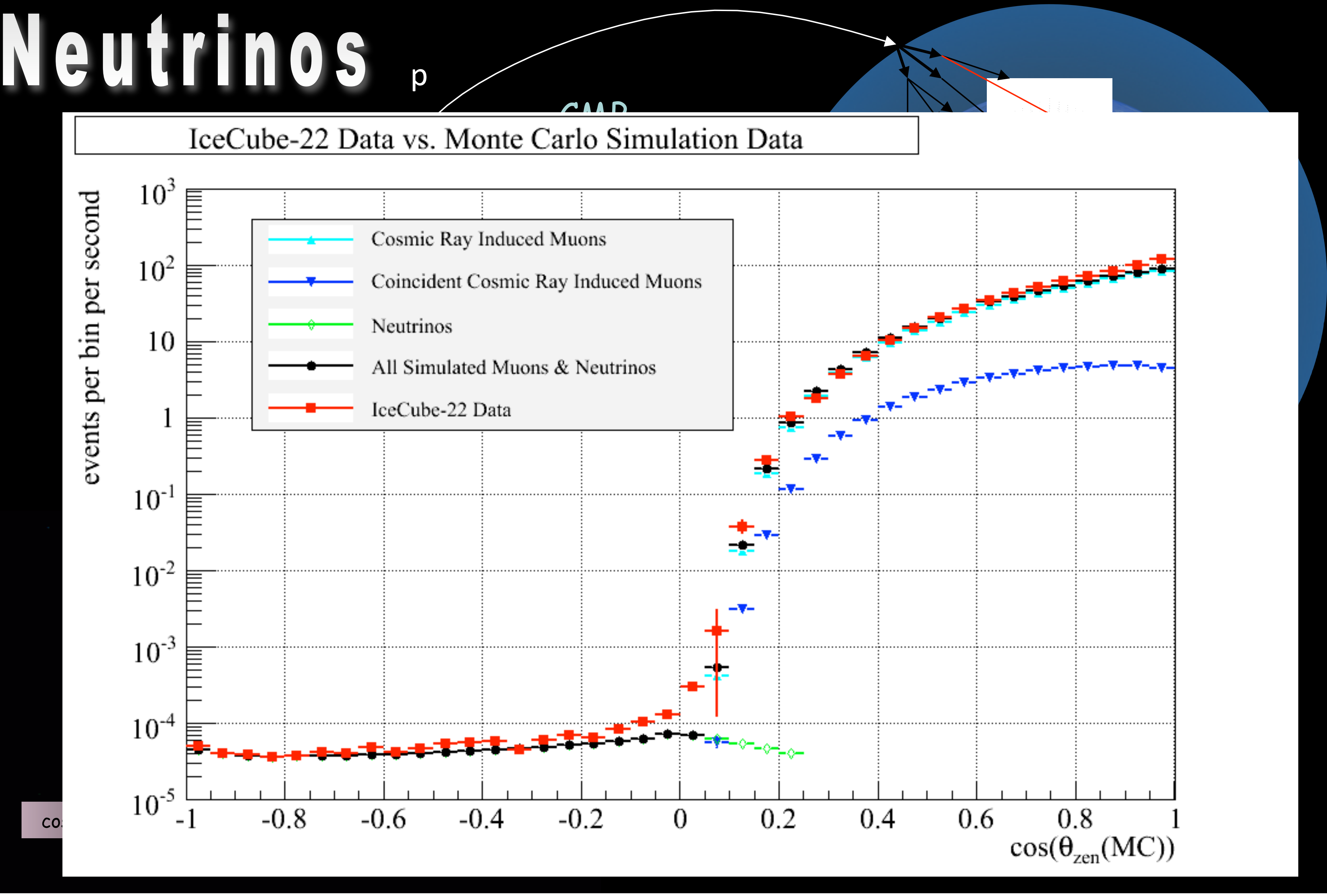
- New variables are a stronger function of energy.
- Use information contained in the waveform instead of simply counting the number of hit phototubes.



Energy Resolution
$\sigma(\log_{10}E) \sim 0.3$

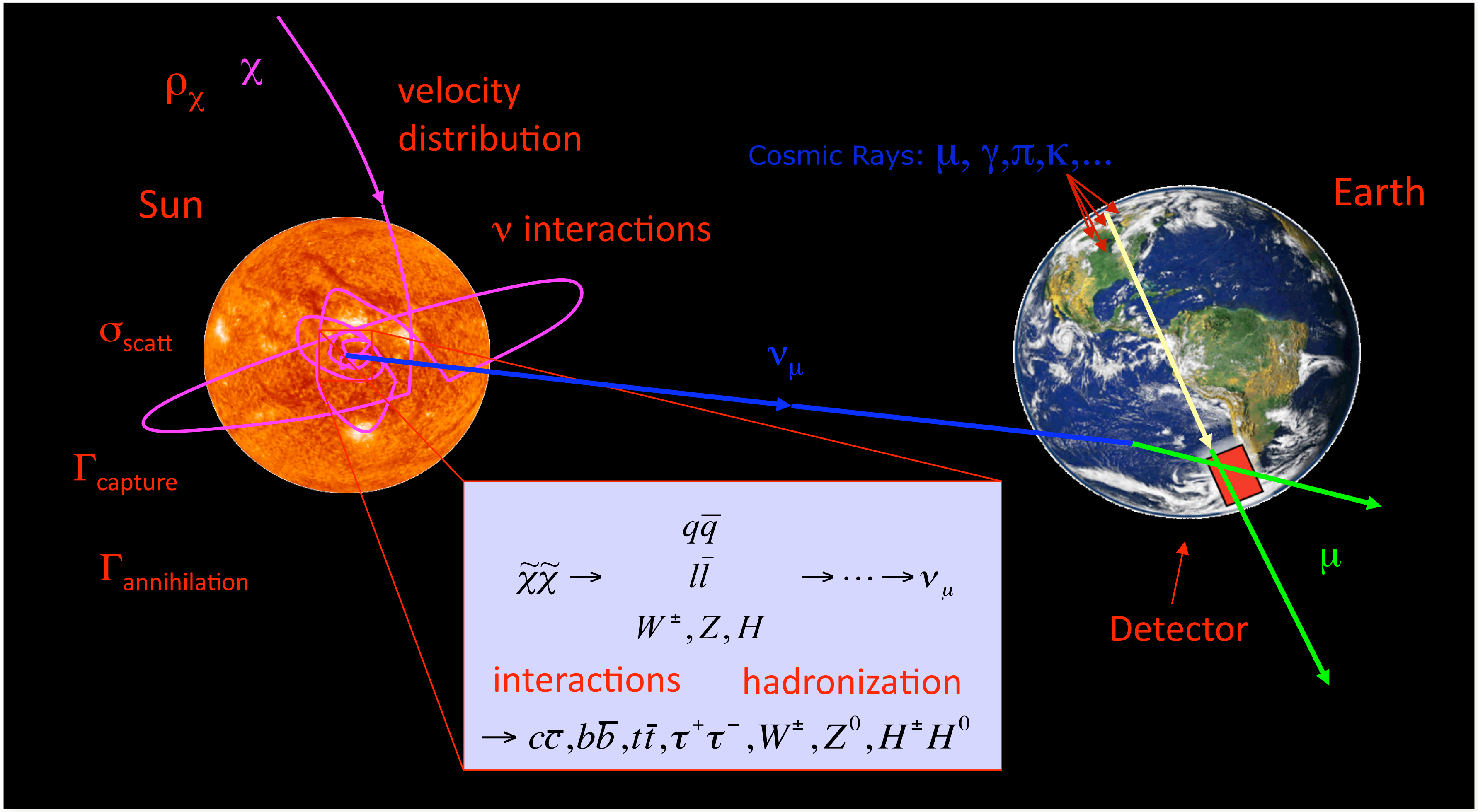
Atmospheric Neutrinos

Atmospheric muons come from above



INDIRECT WIMP SEARCHES

WIMP detection by South Pole Neutrino telescopes



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

Horizontal events very important!

Also look for Wimps trapped in the gravity well of the earth. They will appear to come from the center of the earth.

Indirect vs. Direct Detection

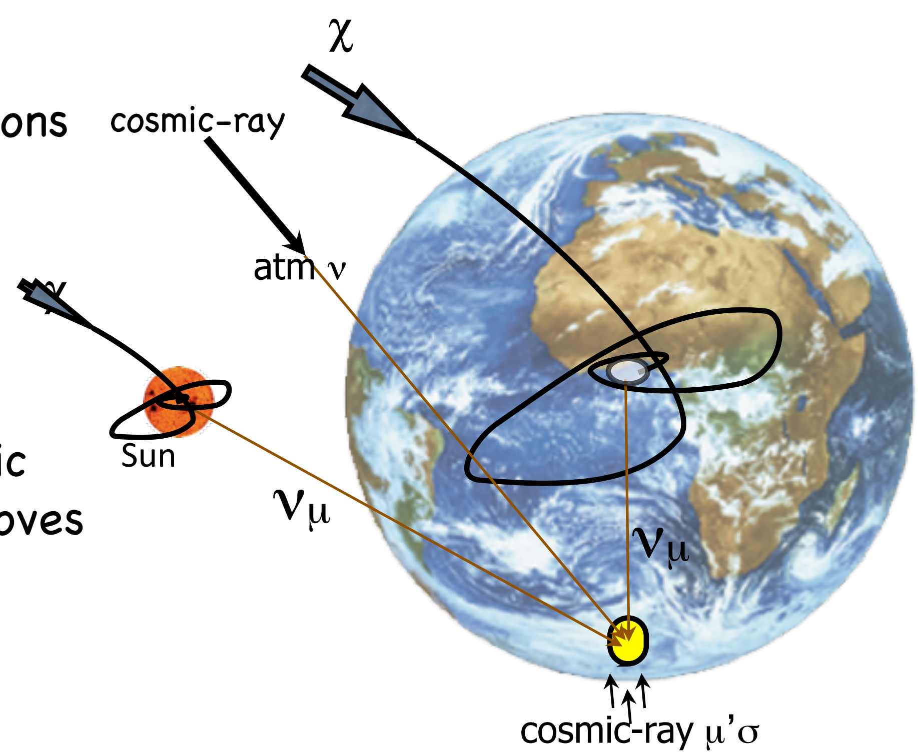
Indirect detection is:

•more sensitive to spin-dependent detection
(the sun is a huge proton target for which spin dependent interaction is important)

•less sensitive to spin-independent interactions
(A2 coherence not present in hydrogen)

•more sensitive to low WIMP velocities
(efficient gravitational trapping)

•may sample regions with higher WIMP relic density as gravitational well (Sun, Earth) moves in space and time



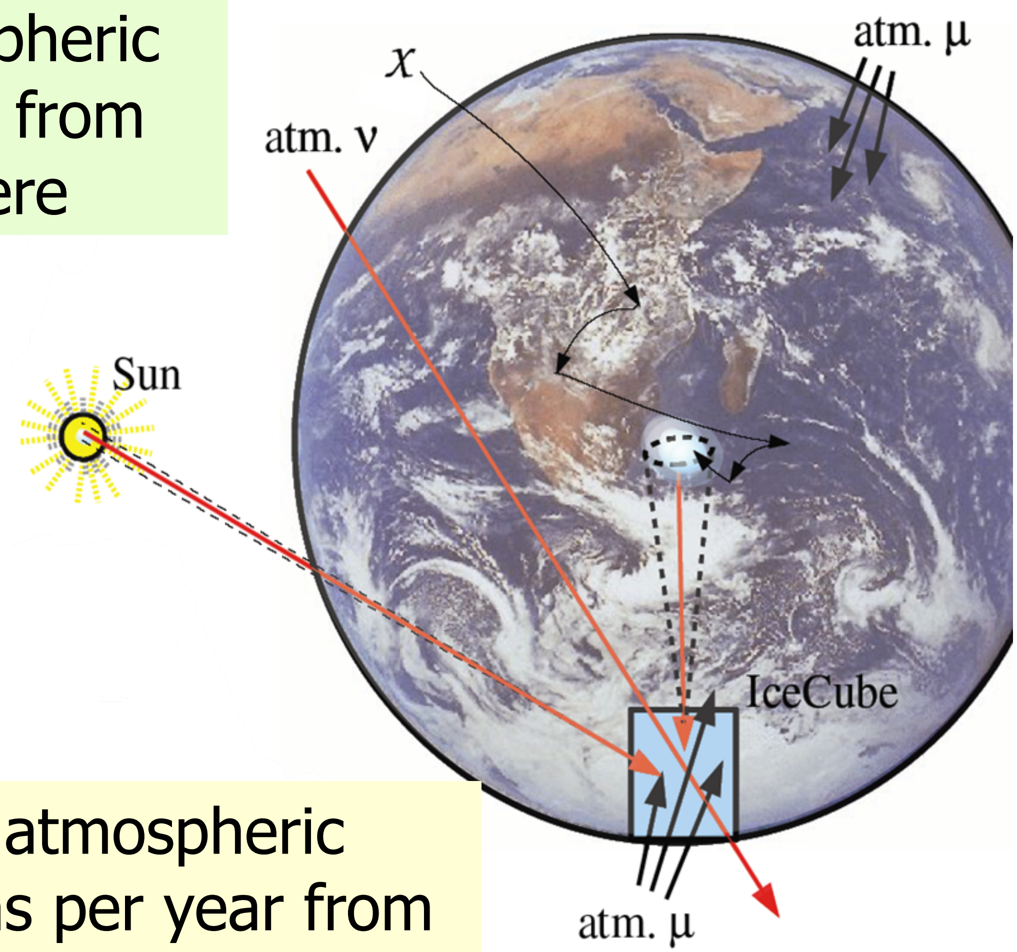
Backgrounds for WIMPs

BG

A few 1000 atmospheric neutrinos per year from northern hemisphere

signal

Max. a few neutrinos per year from WIMPs



BG

~10^9 atmospheric muons per year from southern hemisphere

Solar WIMP search

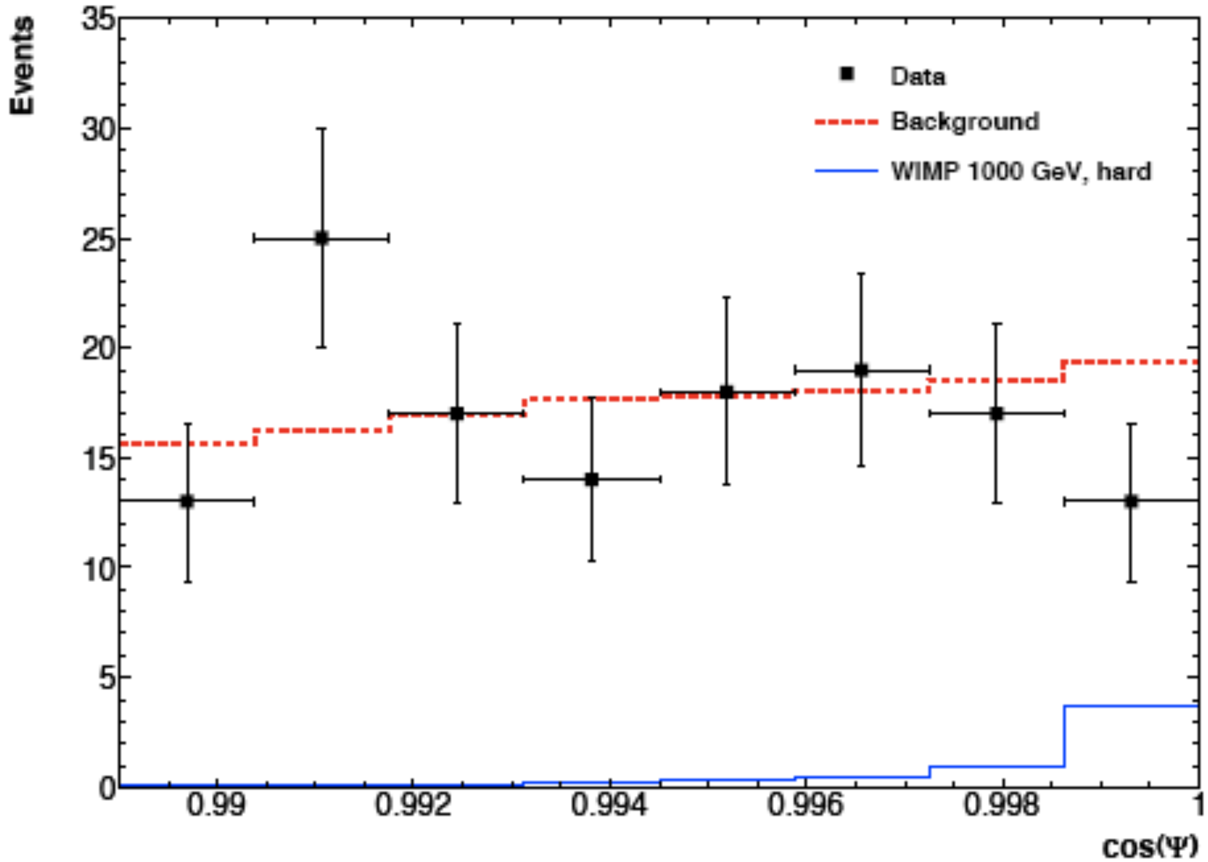
Take pure neutrino sample and look for excess above irreducible atmospheric neutrino background.

•search in bins in space angle from the direction of the Sun

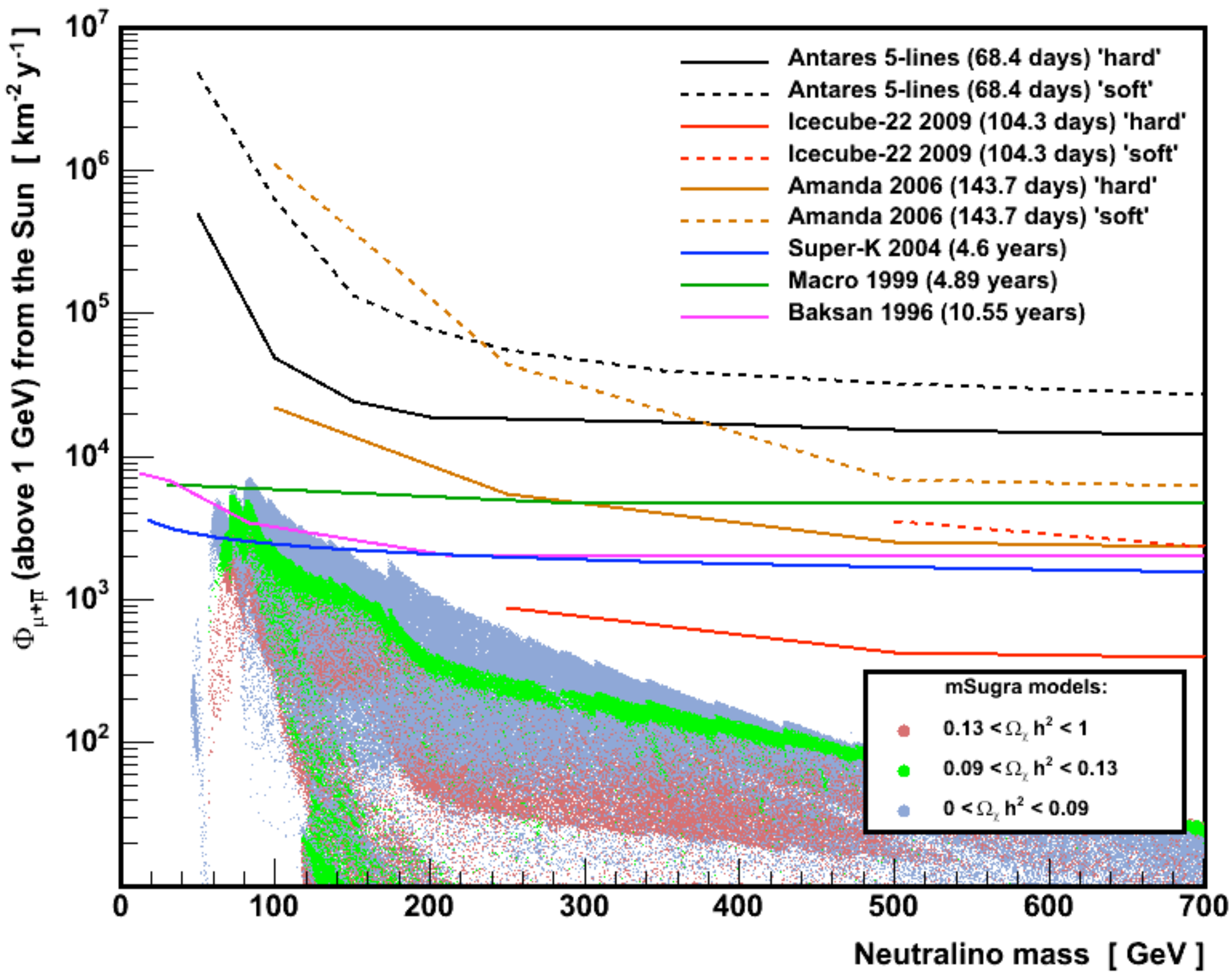
•angular resolution important

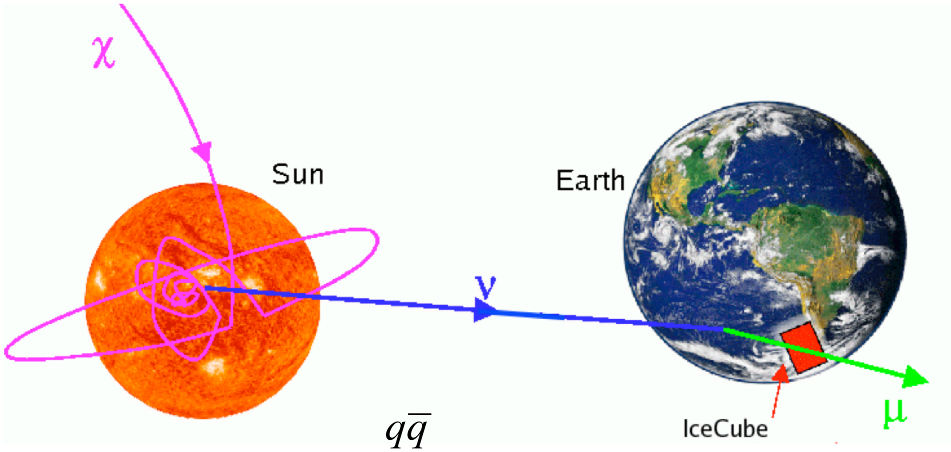
•3° angular resolution >500 GeV for IC22 (better for IC40 and at higher energies)

•was 4°-5° in AMANDA for tracks below 500 GeV



WIMP flux limit summaries





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

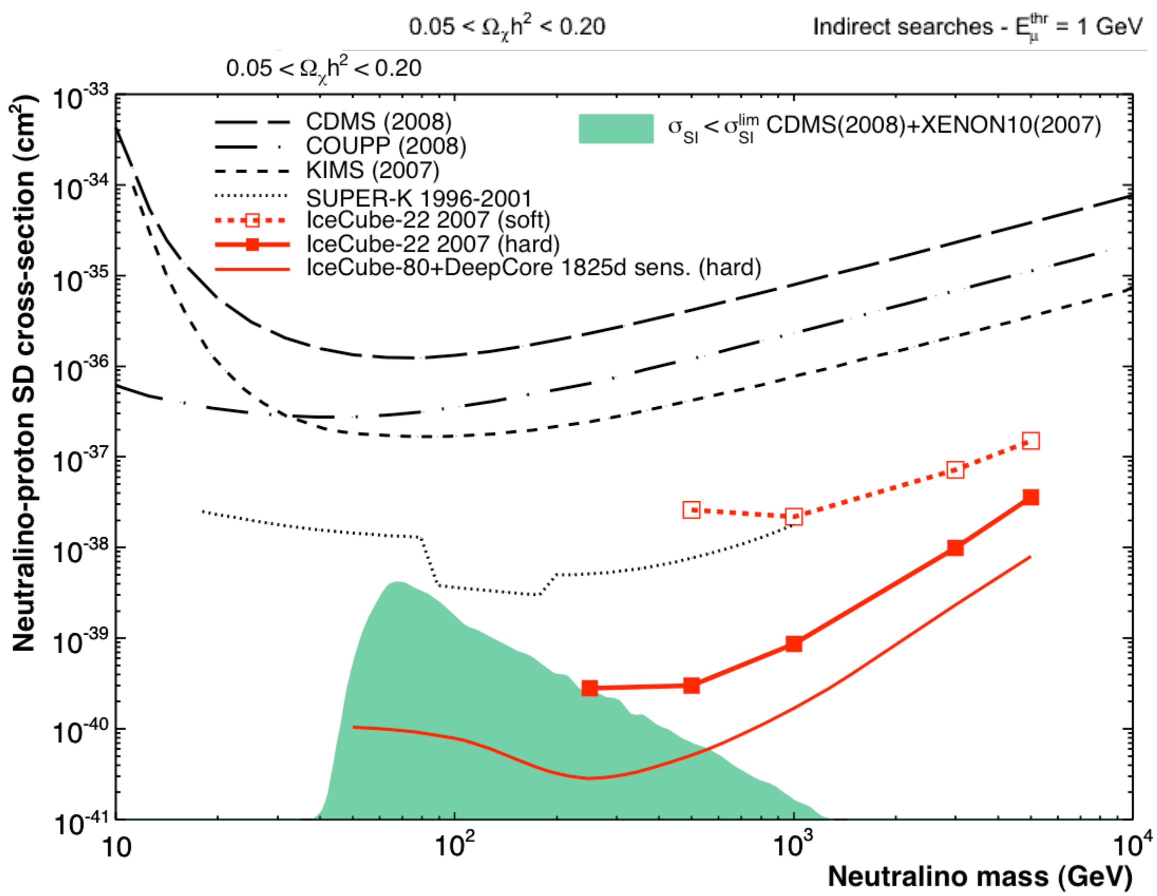
WIMPs

- *annihilating in the gravity well of the Sun*
- *indirect detection*
- *limits shown are spin dependent*

- Set limit on σ_{SD} by assuming $R_{annih} = R_{capture}$, local ρ_{WIMP} = 0.3GeV/cm^3 and Maxwellian v_{WIMP}

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

- Deep core enhancement under construction will greatly enhance sensitivity.

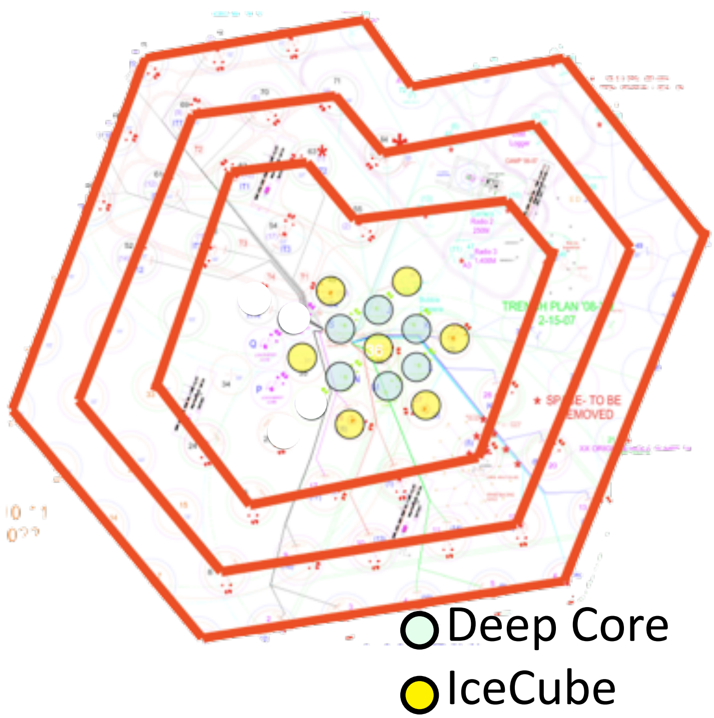


IceCube as an atmospheric muon veto

Rejection rate

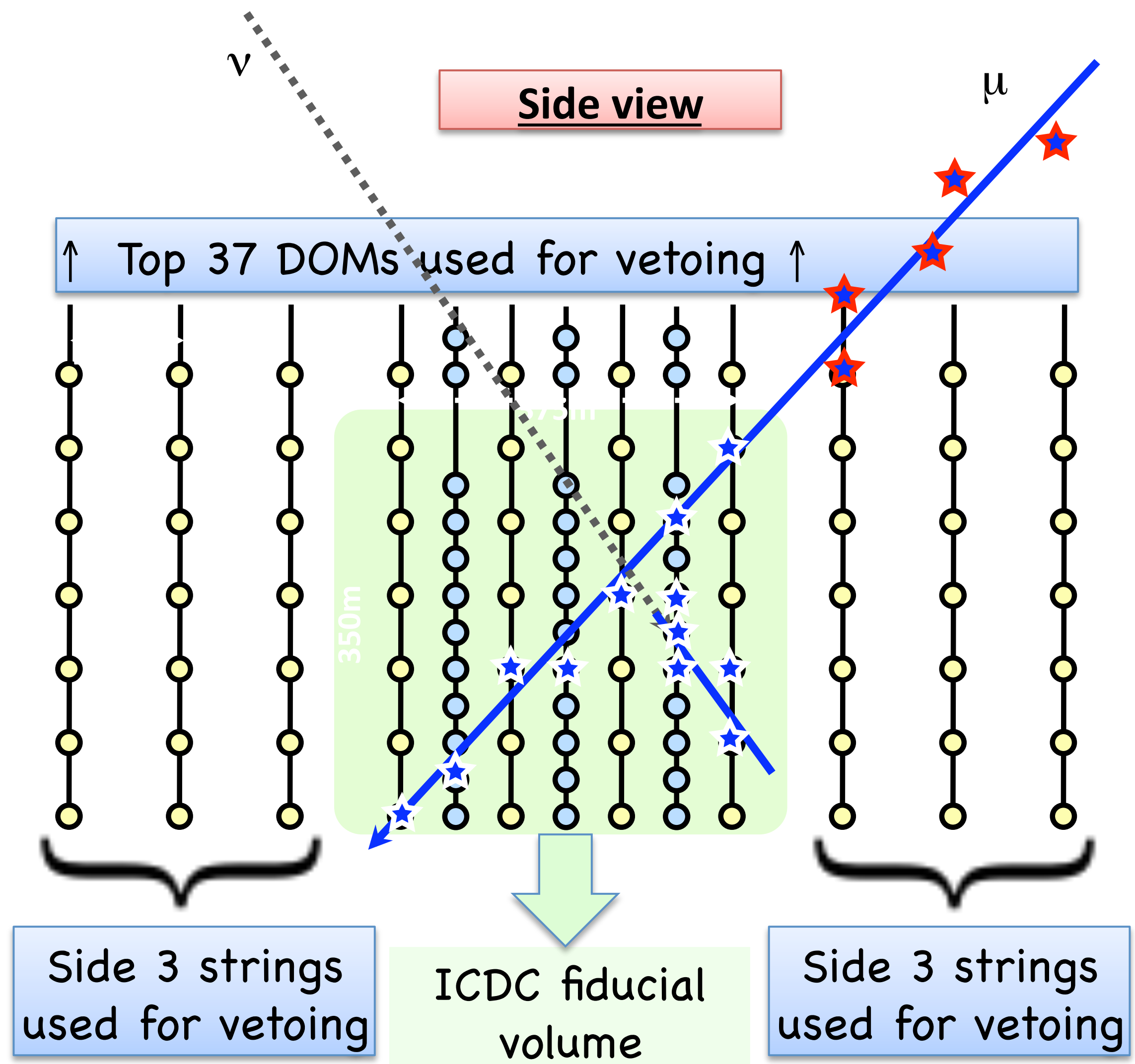
$$\phi(\mu)/\phi(\nu_{\text{atm}}) \simeq 10^6$$

Top view

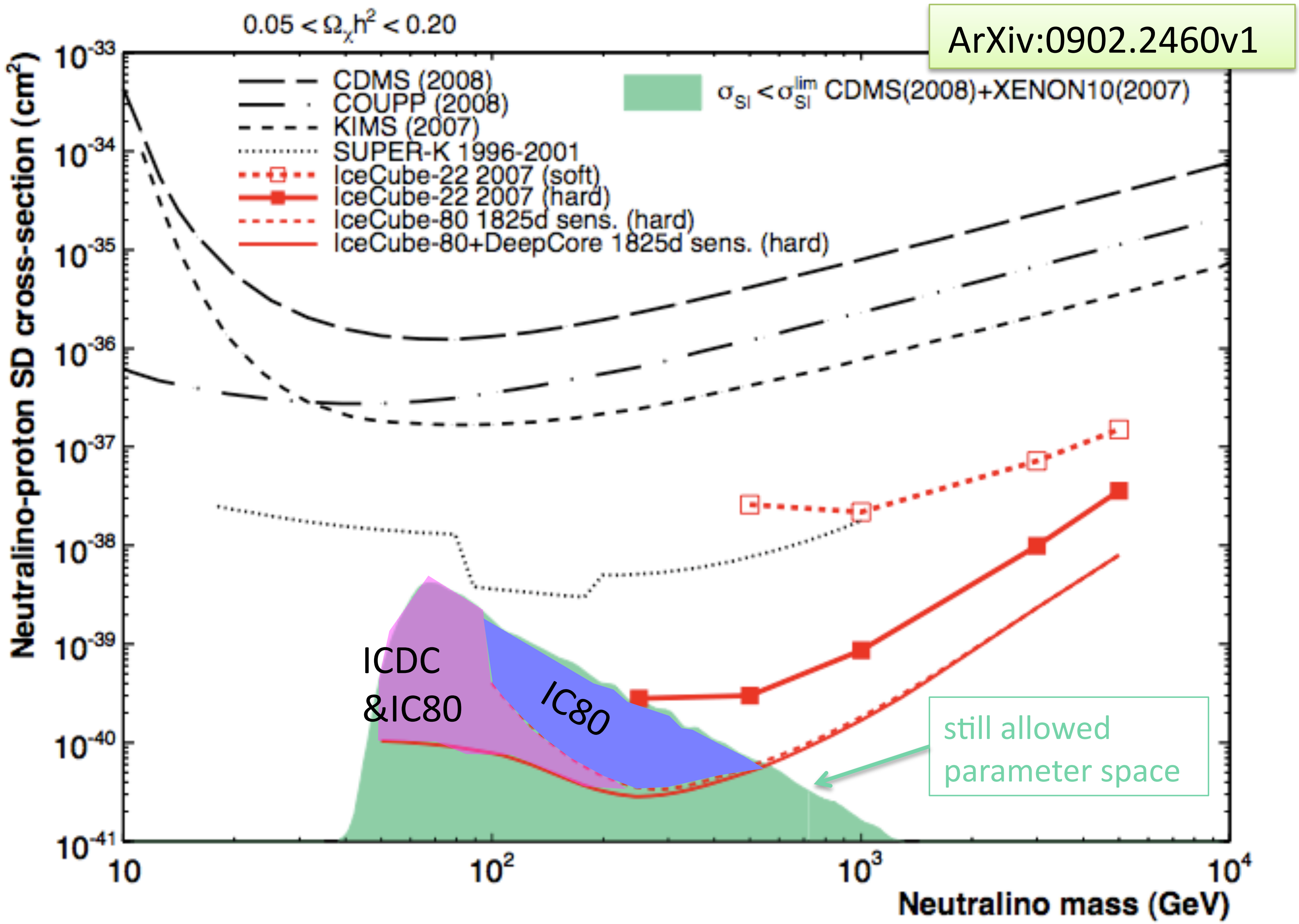


375 m thick active veto:
3 full IceCube string
layers surround ICDC

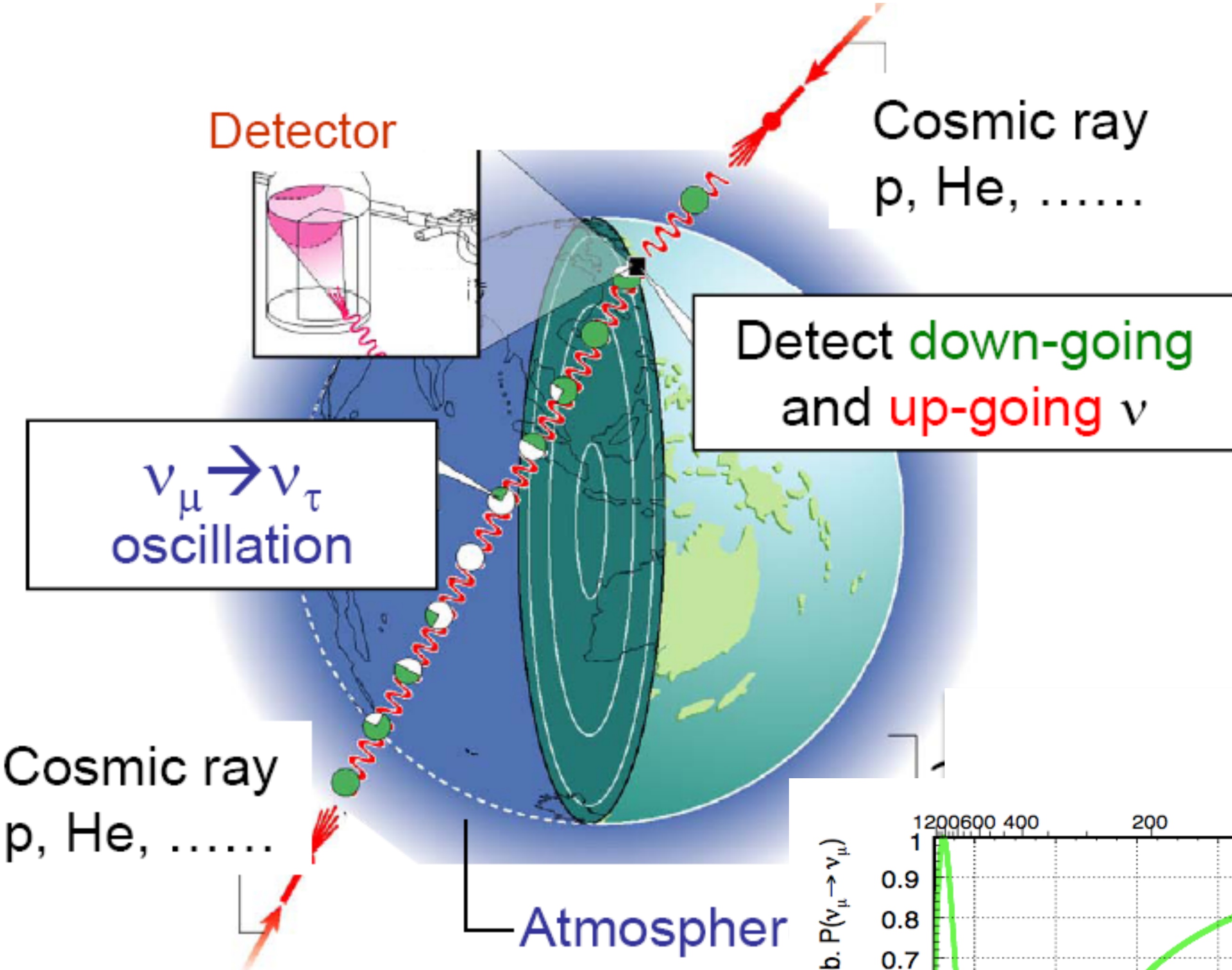
veto allows searches above horizon!

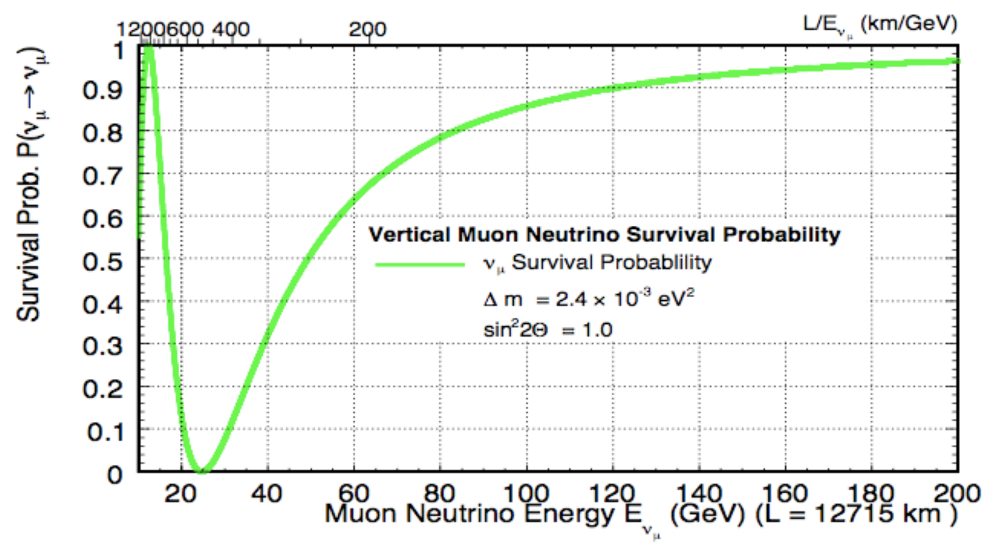


Deep Core & IceCube (5 year) sensitivity!



NUETRINO PROPERTIES



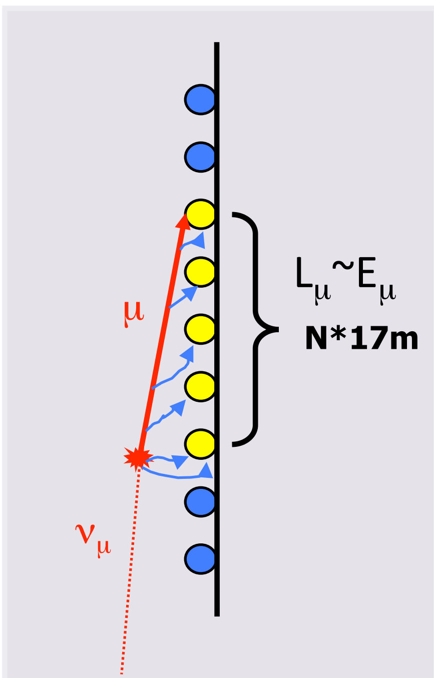


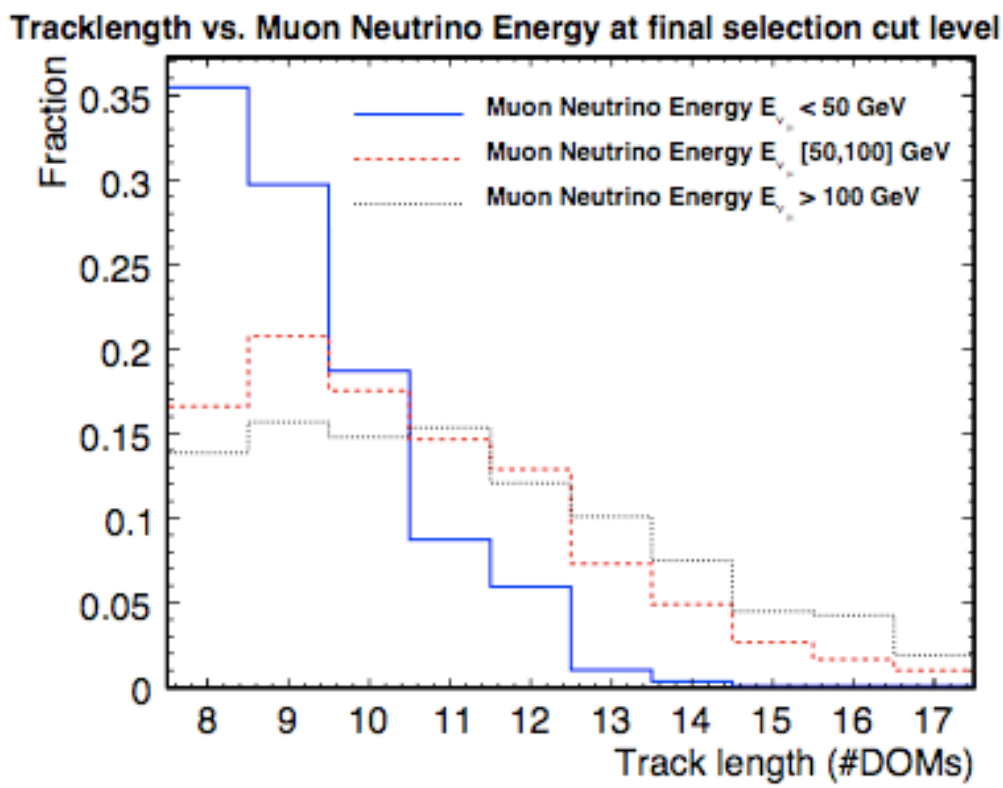
atmospheric neutrino “beam”

Neutrino Oscillations

•17m optical module spacing results in a lower energy threshold for vertical event
•track length used as an energy estimator (5m travel/GeV)

•Deep core enhances low energy sensitivity

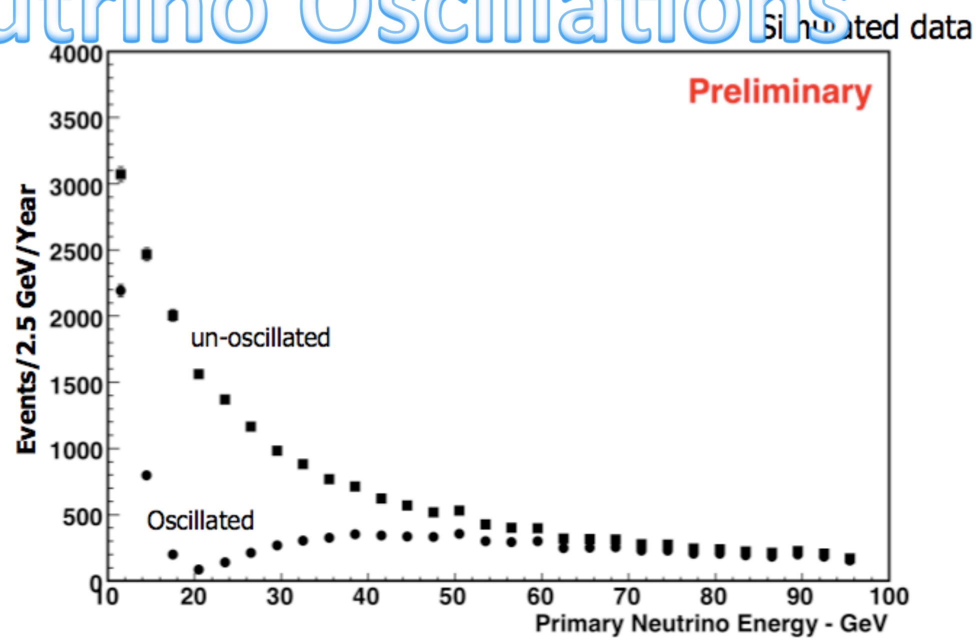


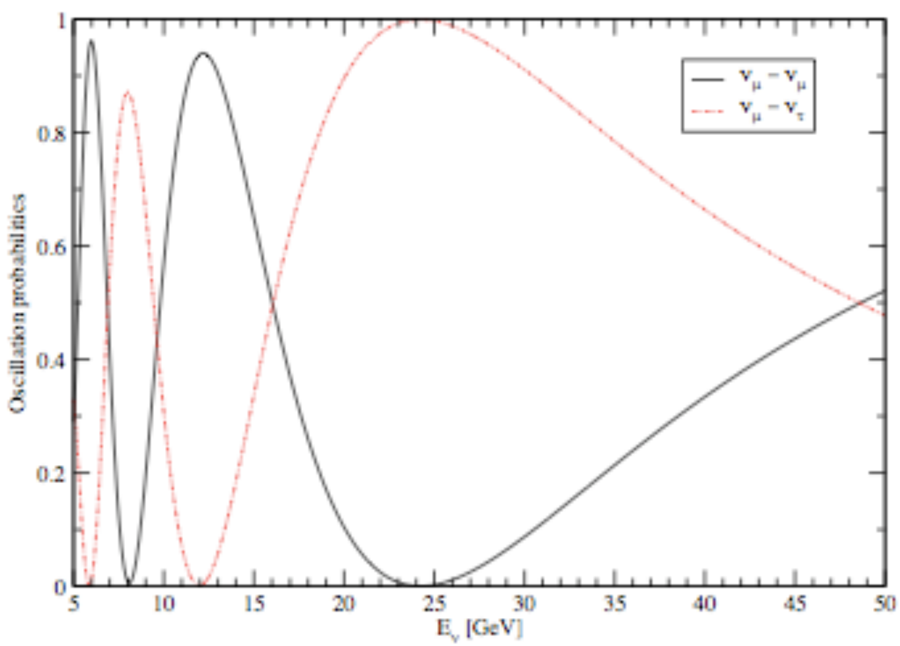


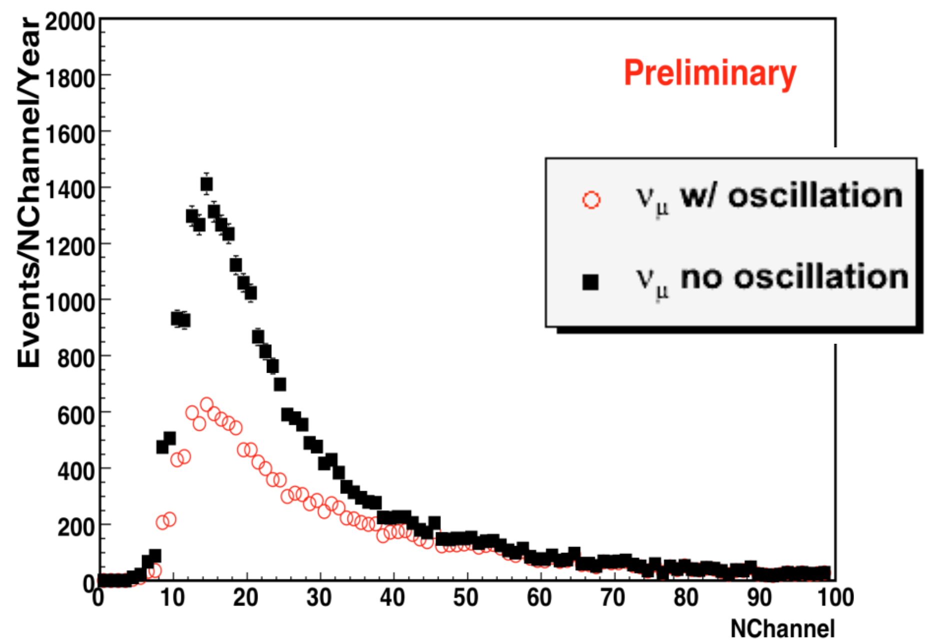
Sensitivity to Neutrino Oscillations

IceCube with Deep Core

- ν_μ disappearance for cos ϕ <-0.6 for 1 year of IceCube with the Deep Core
- Conversion of the disappearing $\nu\mu$ to $\nu\tau$ manifests as an increase of low energy cascade events in DeepCore; would be the largest sample of $\nu\tau$ ever collected and possible first appearance of $\nu\tau$ due to oscillations

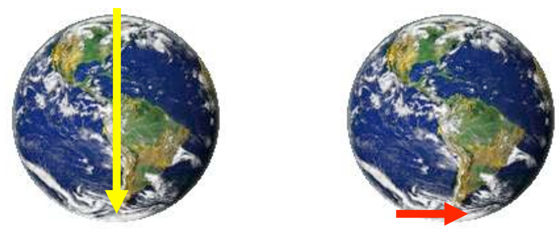




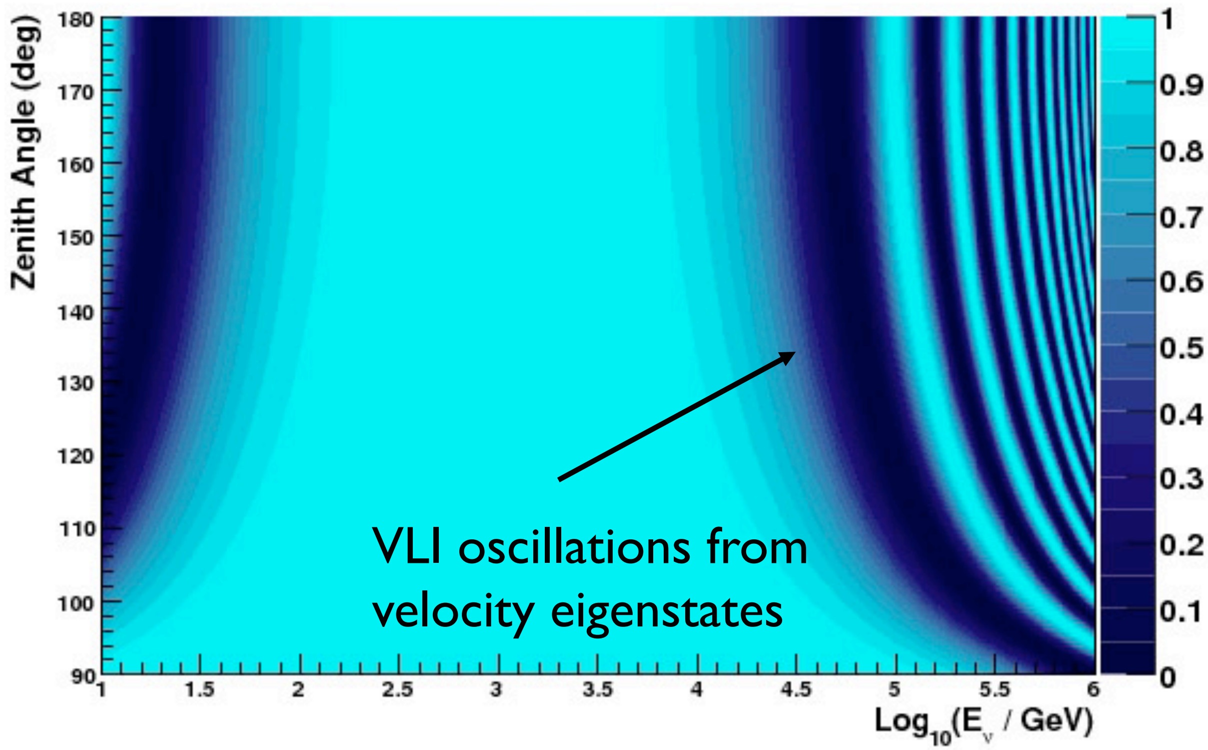


High Energy Neutrino Oscillations

$$P_{\nu_\mu \to \nu_\mu}(\text{maximal}) = 1 - \sin^2\left(\frac{\Delta m^2 L}{4E} + \frac{\Delta c}{c}\frac{LE}{2}\right)$$



- For E > 100 GeV and m_ν < 1 eV, Lorentz $\gamma > 10^{11}$
- Oscillations are a sensitive quantum-mechanical interferometer — small shifts in energy can lead to large changes in flavor content



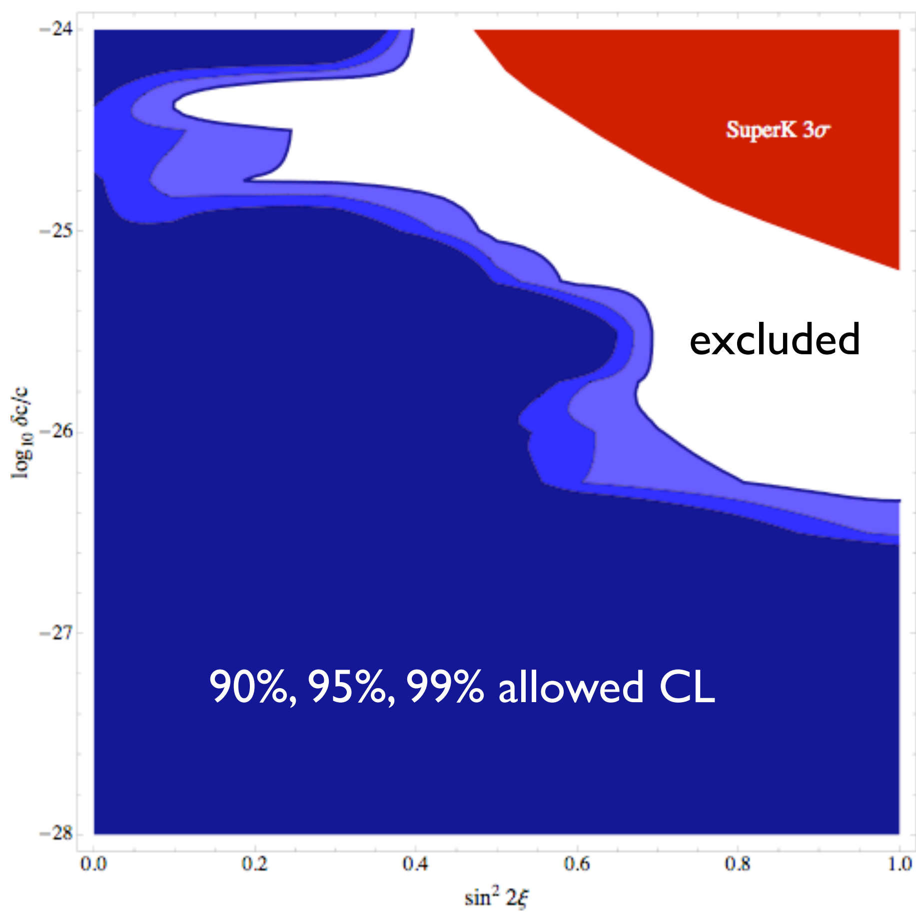
maximal mixing, $\delta c/c = 10^{-27}$

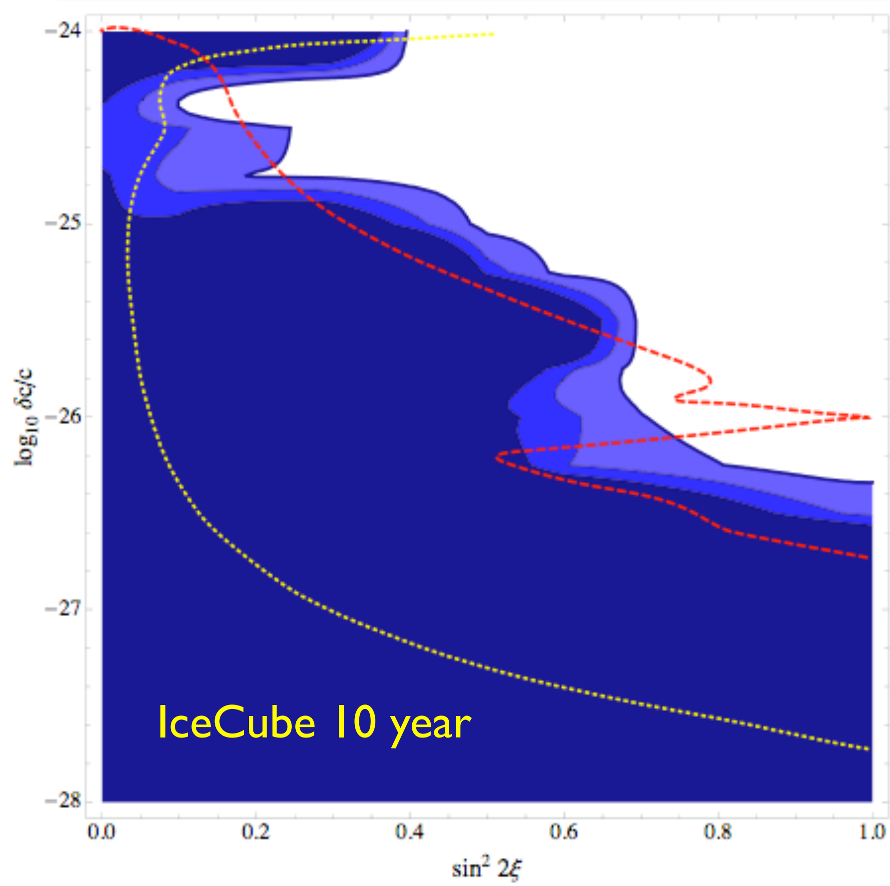
Example: Violation of Lorentz Invariance

•VLI introduces velocity eigenstates distinct from mass and flavor
•new mixing angle ξ and phase η

Limits on Violation of Lorentz Invariance assuming maximal mixing:

- SuperK+K2K limit*:
  $\delta c/c < 1.9 \times 10^{-27}$ (90%CL)
- AMANDA II analysis:
  $\delta c/c < 2.8 \times 10^{-27}$ (90%CL)
- IceCube: sensitivity of $\delta c/c \sim 10^{-28}$
  Up to 700K atmospheric ν_μ in 10 years





Astrophysical ν beams

•Neutrinos produced in astrophysical beam dumps (active galactic nuclei) will have flavor ratios of ν_e:ν_μ:ν_τ=1:2:0. (ν_τ contribution from prompt flux of heavy flavor will be small).
•Ratio observed at Earth should be of ν_e:ν_μ:ν_τ=1:1:1. since $\Delta m^2 L/4E>10^7$

Order of magnitude:

type	L/E	$t_{proper} \sim (L/c)(m_\nu/E)$
CERN SpS/WANF	500 m/25 GeV	3 attoseconds
Stopped μ (LAMPF)	30 m/ 40 MeV	130 attoseconds
NUMI	735 km/ 4 GeV	30 femtoseconds
Reactor (KamLAND)	150 km/5 MeV	800 femtoseconds
Atmospheric	10,000 km/1 GeV	2 picoseconds
Sun	150,000,000 km/5 MeV	800 nanoseconds
GZK	1 Gpc/100 PeV	50 milliseconds
SN-1987a	50 kpc/15 MeV	1 hour

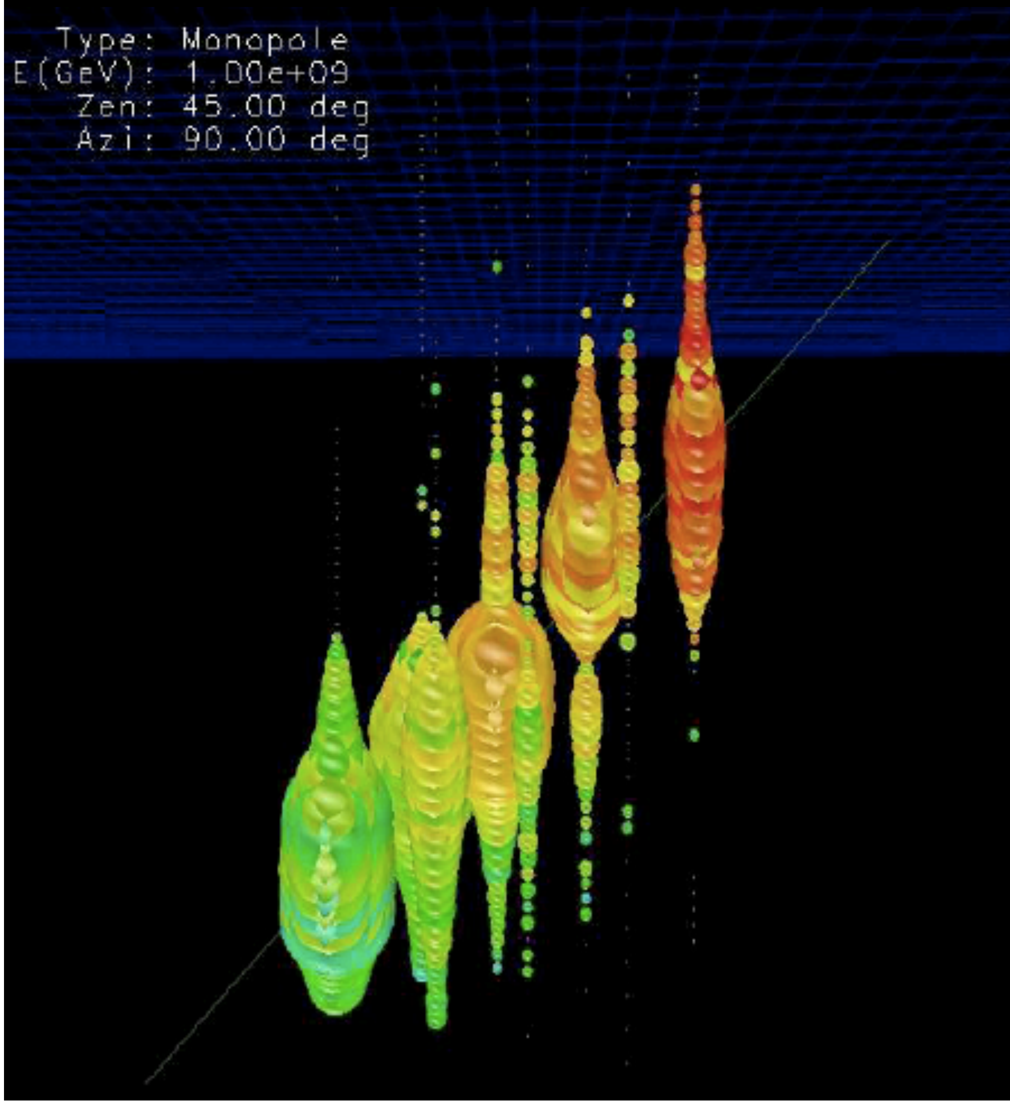
Differences imply:

• ν_e:ν_μ:ν_τ=1:2:0 → neutrino mass differences are nonzero only in the presence of matter
•neutrino decay would alter the flavor mix

In addition, neutrino cross sections at high energy can be measured through their absorption in the Earth.

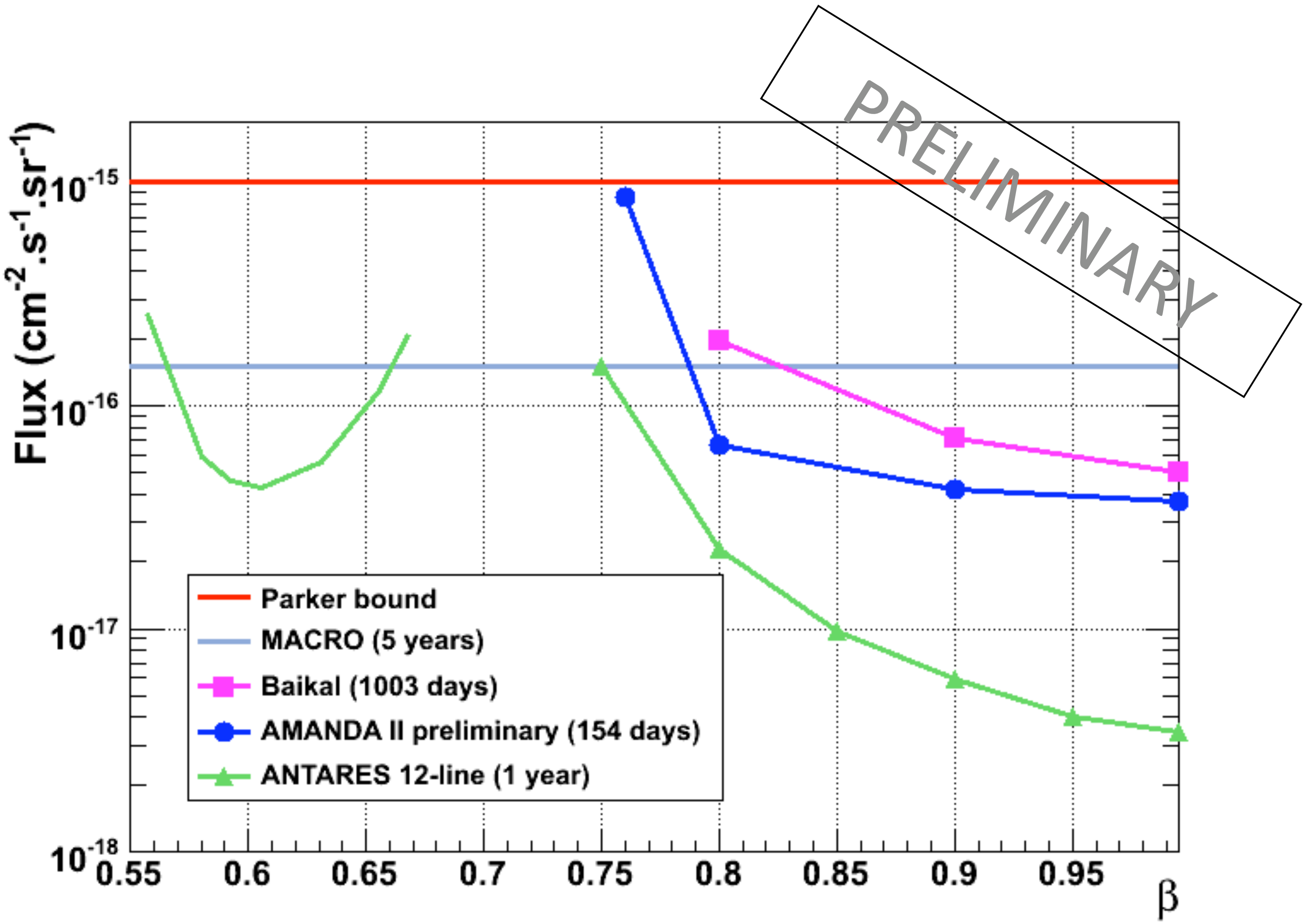
OTHER EXOTICS

Magnetic monopoles



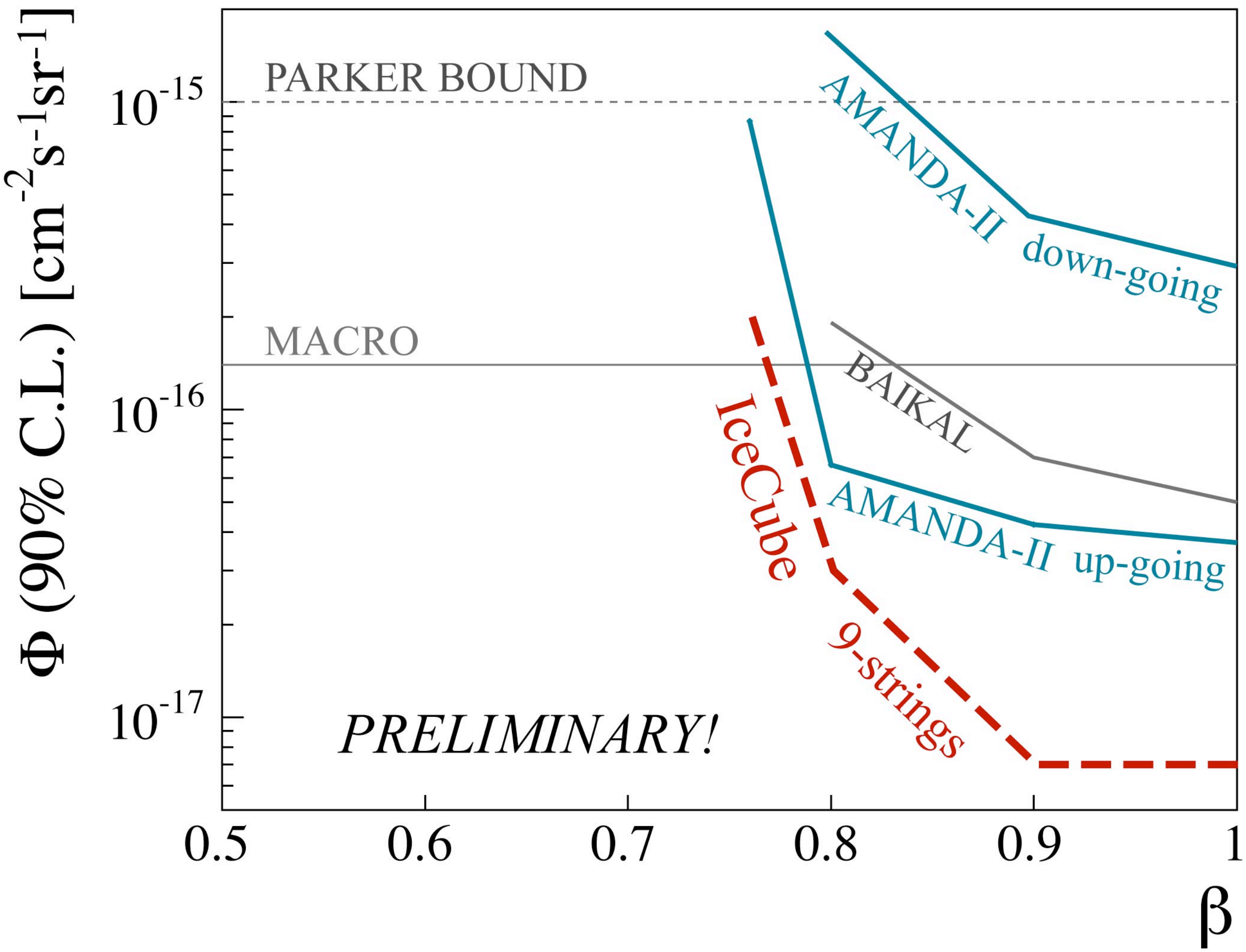
- Look for relativistic monopoles above the Cerenkov threshold (>0.75c for direct monopoles, >0.52c for delta electrons)
- Extremely bright events-8000 times brighter than a muon
- Allows a search for downgoing as well as upgoing monopoles
- Mass related to GUT scale-Relativistic for m<10^14 GeV

Preliminary 90% C.L. sensitivity with the 12-line ANTARES detector for up-going magnetic monopoles



~1.1 expected background events after one year of 12-line ANTARES data taking.

Monopole limits

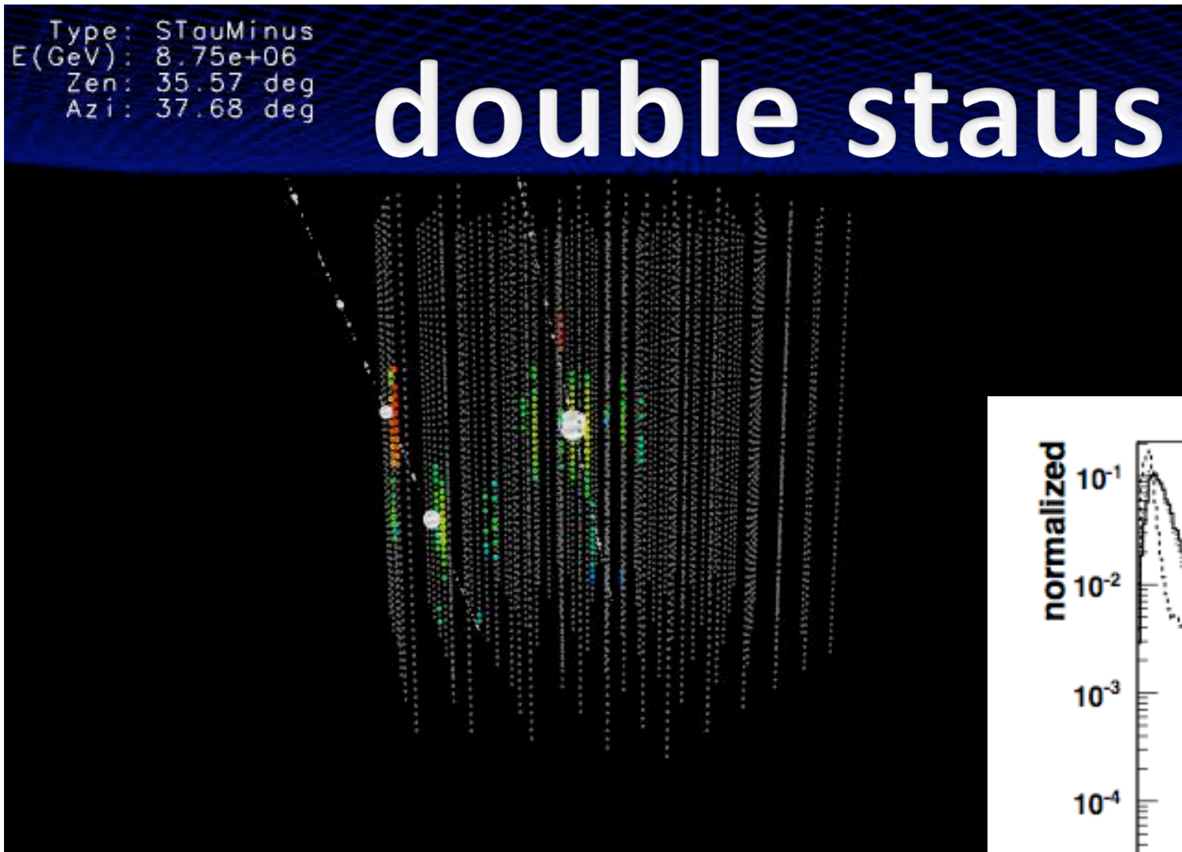


Down-going valid for $m>10^8$ GeV

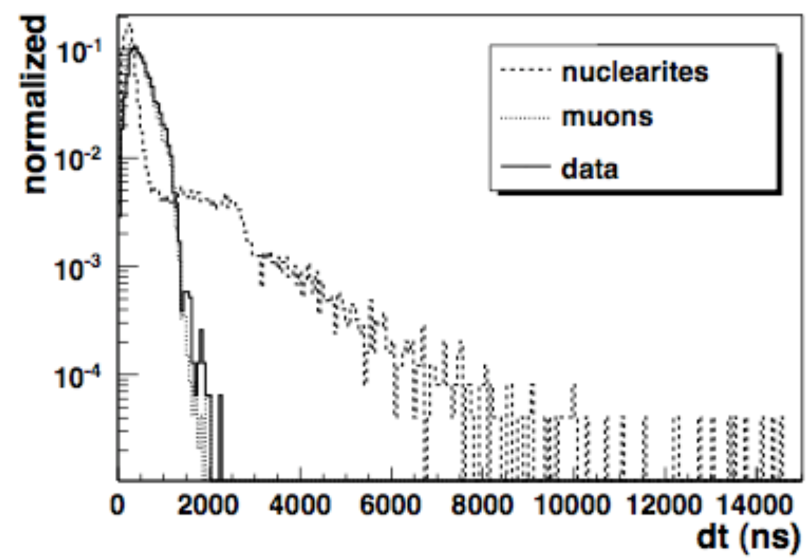
Upgoing valid for $m>10^{11}$ GeV

IceCube relativistic monopole limit will supersede the best AMANDA limit with only 9 strings!

OTHER EXOTICA



nuclearites



Direct detection of supersymmetric particles in neutrino telescopes. by I.F.M. Albuquerque, G. Burdman, and Z. Chacko , arXiV/0605120

Summary and Outlook

- New generation of neutrino telescopes of unprecedented scale coming on line.
- Construction of ANTARES is complete and larger scale KM3Net Mediterranean detector is in R&D phase.
- Construction of IceCube on schedule, and the addition of 19 new IceCube strings in the austral summer of 2008-2009 brings the total to 59. Plans for a low energy enhancement have progressed quickly.
- High energy neutrino telescopes may be able to study neutrino oscillations at high energies.
- IceCube indirect dark matter searches will be competitive with direct searches in a few years.
- Detection of GZK neutrino flux may be on the horizon.
- Thanks: Henrike Wissing, Albrecht Karle, Gabriela Pavalas, Zhan Dzhilkibaev, Gordon Lim, Alex Olivas, David Saltzberg, Carsten Rott, Darren Grant, Doug Cowen, Vincenzo Flaminio

Oscillation effects on high-energy neutrino fluxes from astrophysical hidden sources.
O. Mena , I. Mocioiu , S. Razzaque . Dec 2006. 10pp.
Published in Phys.Rev.D75:063003,2007. e-Print: astro-ph/0612325

Ultrahigh-energy neutrino flux as a probe of large extra-dimensions.
J. Lykken , O. Mena , S. Razzaque May 2007. 5pp. JCAP 0712:015,2007.

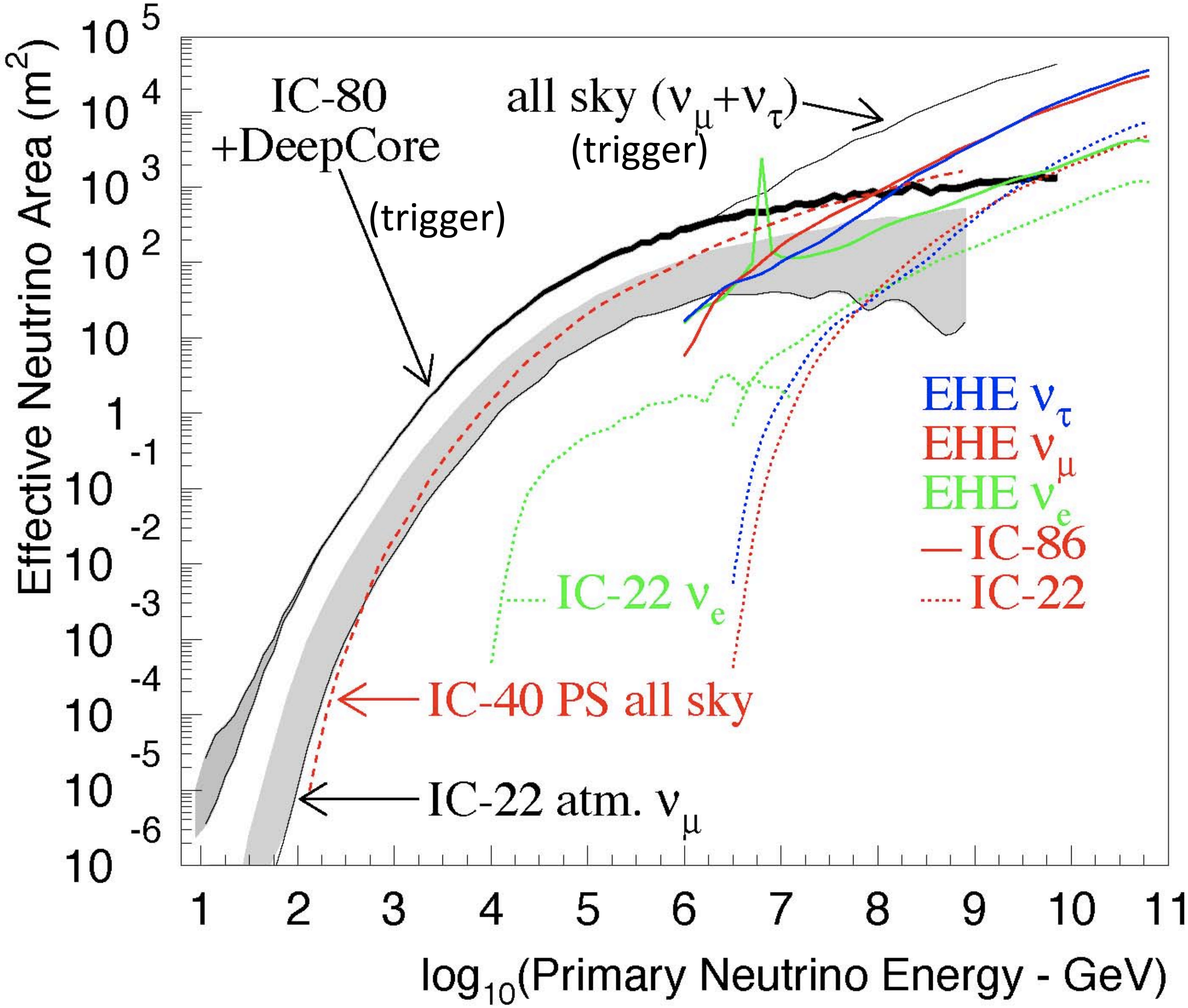
Neutrino mass hierarchy extraction using atmospheric neutrinos in ice.
O. Mena , I. Mocioiu, S. Razzaque . Mar 2008. 10pp.
Published in Phys.Rev.D78:093003,2008. e-Print: arXiv:0803.3044 [hep-ph]

1-3 leptonic mixing and the neutrino oscillograms of the Earth.
E K Akhmedov, M. Maltoni, A. u. Smirnov. Dec 2006. 51pp.
Published in JHEP 0705:077,2007. e-Print: hep-ph/0612285

Neutrino properties from high energy astrophysical neutrinos.
Sandip Pakvasa . Dec 2004. 13pp. Nucl.Phys.Proc.Suppl.137:295-304,2004.

Sensitivity to theta(13) and delta in the decaying astrophysical neutrino scenario.
J. F. Beacom, N. F. Bell, D. Hooper , S.Pakvasa , T. J. Weiler Sep 2003. 3pp.
Published in Phys.Rev.D69:017303,2004. e-Print: hep-ph/0309267

Neutrino effective areas



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

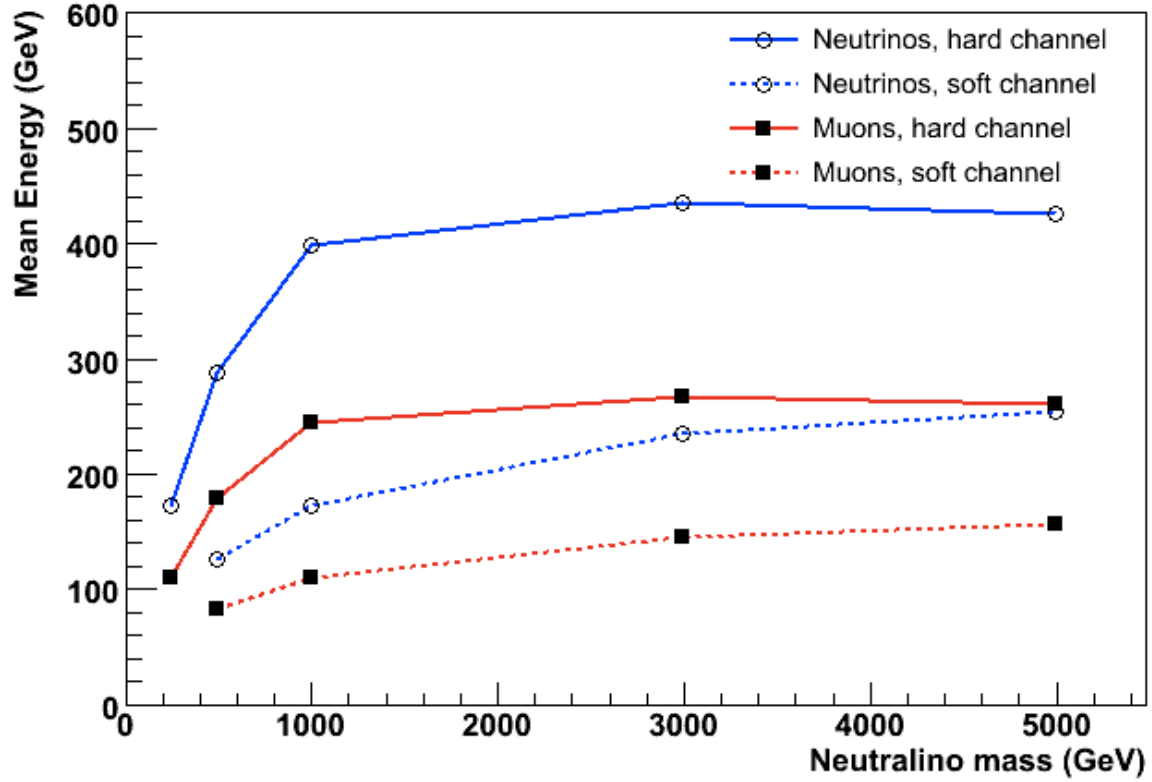
Deep Core lowers threshold from 100 GeV to 10 GeV.

Effective area for ν_μ

Strong rise with energy:

- $\sigma \propto E_\nu$
- Increase of muon range with energy up to PeV

Solar WIMP signal



Soft: $E_\mu \sim 0.01M_\chi - 0.06M_\chi$

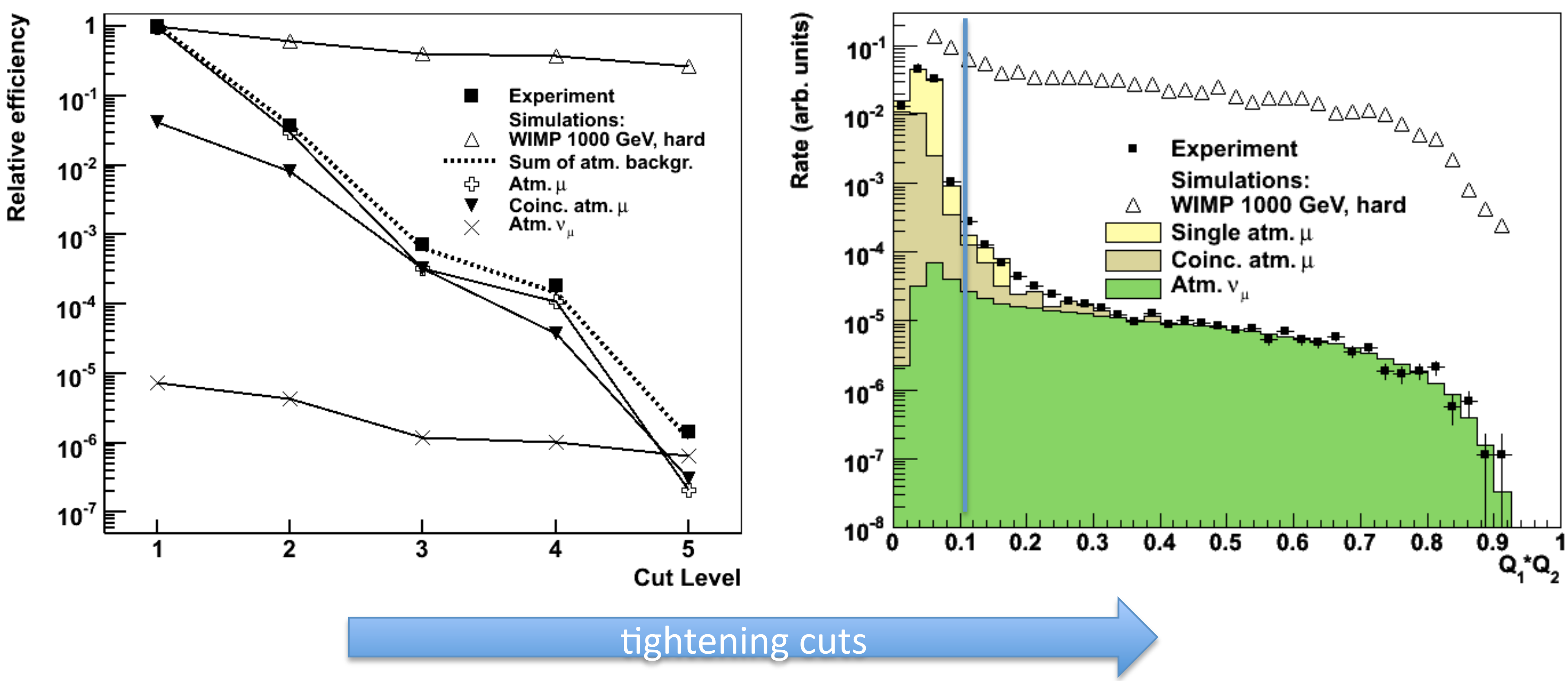
Hard: $E_\mu \sim 0.03M_\chi - 0.3M_\chi$

- signals simulated with WIMPSIM (Blennow, Edsjo, Ohlsson 2008) based on DarkSUSY
- 5 masses simulated: 250, 500, 1000, 3000 and 5000 GeV
- 2 annihilation channels considered
  - Hard W+W-
  - $b\bar{b}$ from secondaries
- full propagation through the Sun is simulated, absorption in the Sun important above a few hundred GeV
- 3 flavor oscillations are accounted for
- IceCube optimized for E_ν>1 TeV

IceCube analysis with 22 string configuration

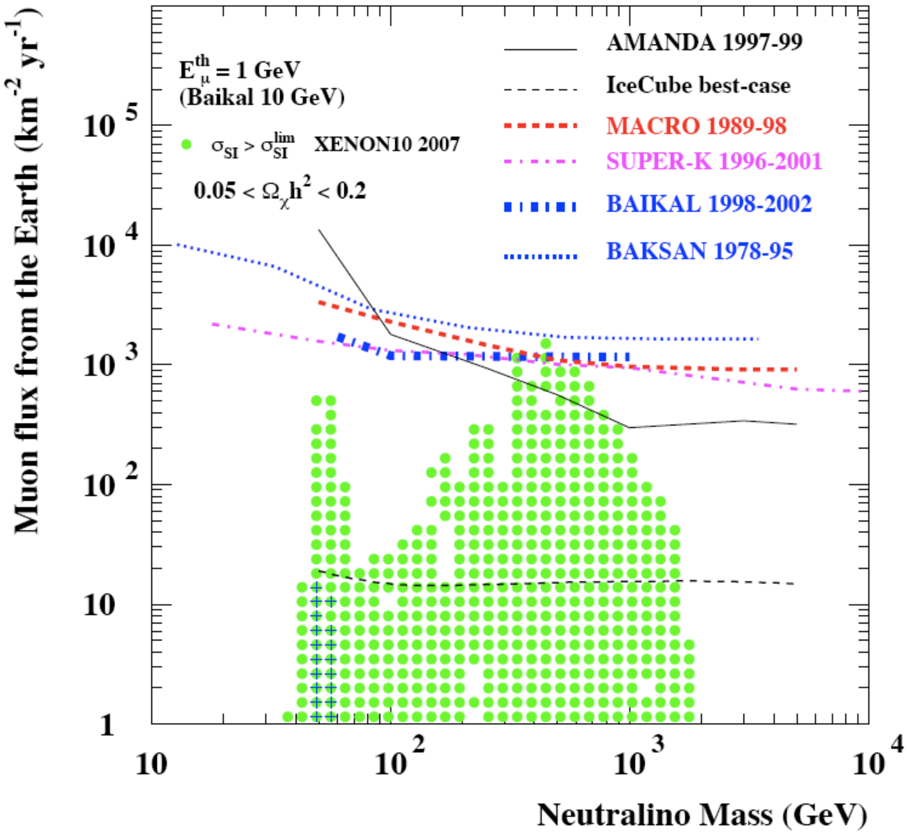
•data taken from April 2007-April 2008
•look for excess of muons from WIMP annihilations in the Sun
•requirement that Sun be below horizon limits analysis to 104 days livetime

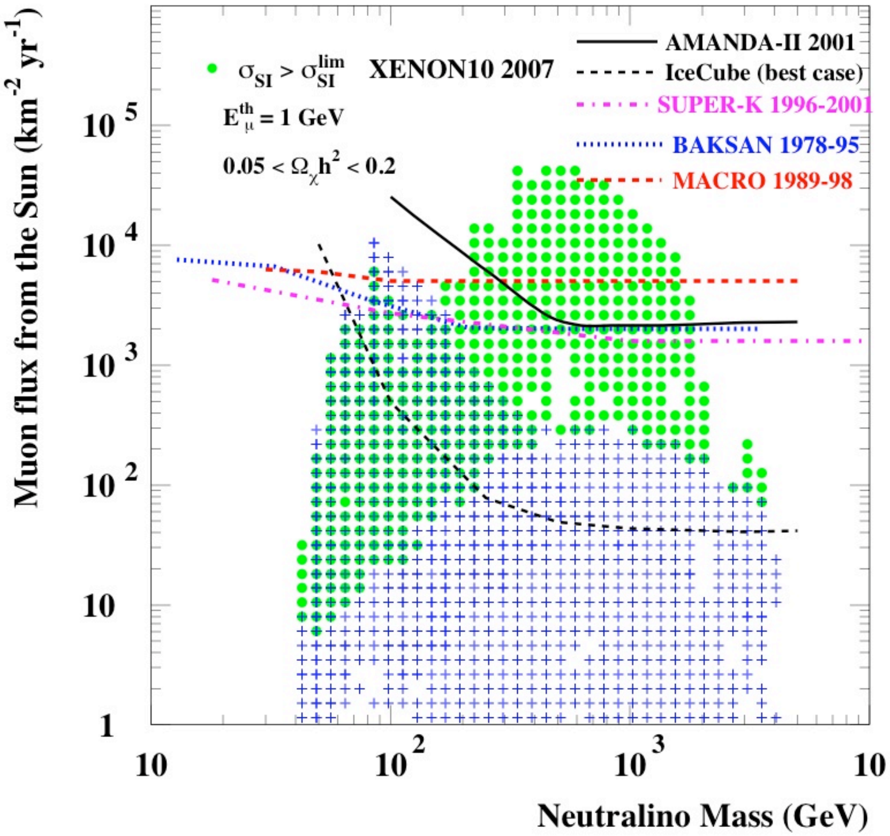
•10^6 background rejection needed



Earth WIMPs

Solar WIMPs



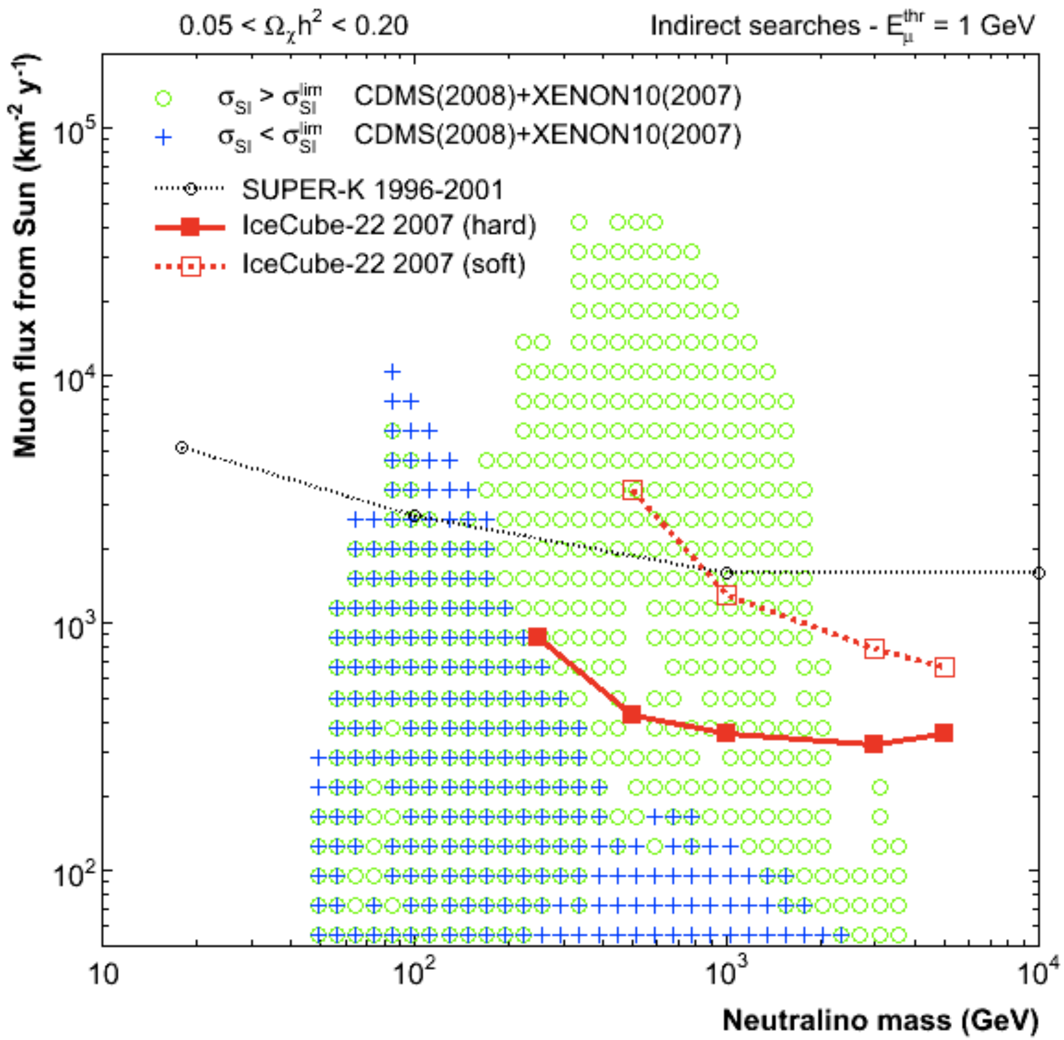


o Excluded by CDMS + XENON10

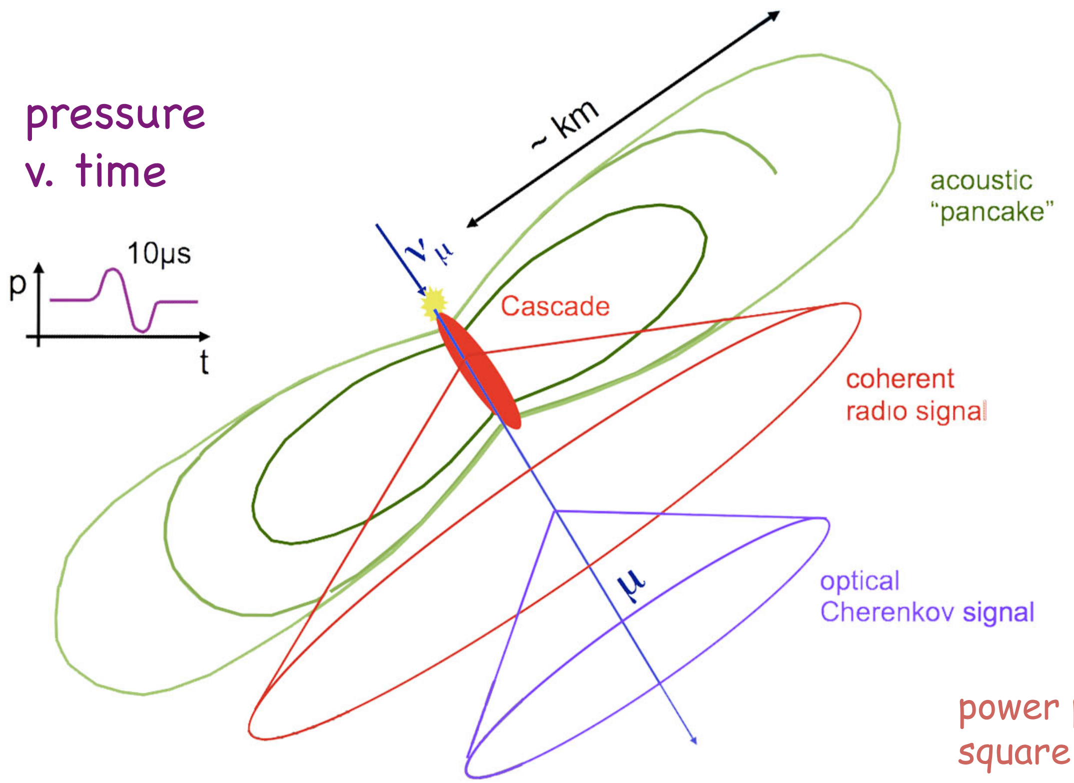
+ allowed by CDMS + XENON10

Muon Flux limits from the Sun

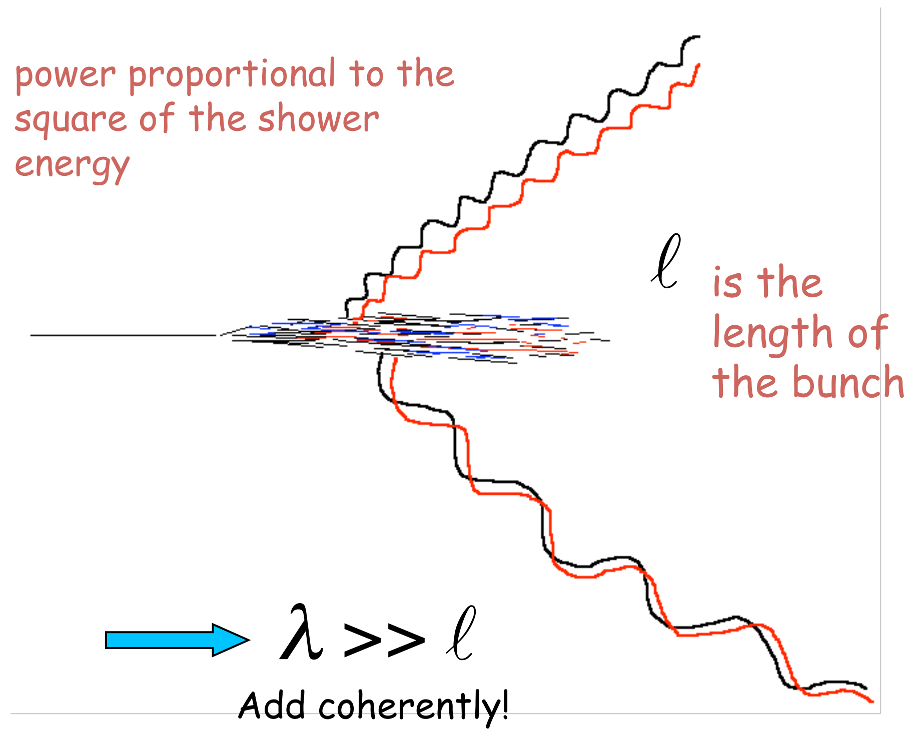
from IceCube 22



The future: a high energy extension?

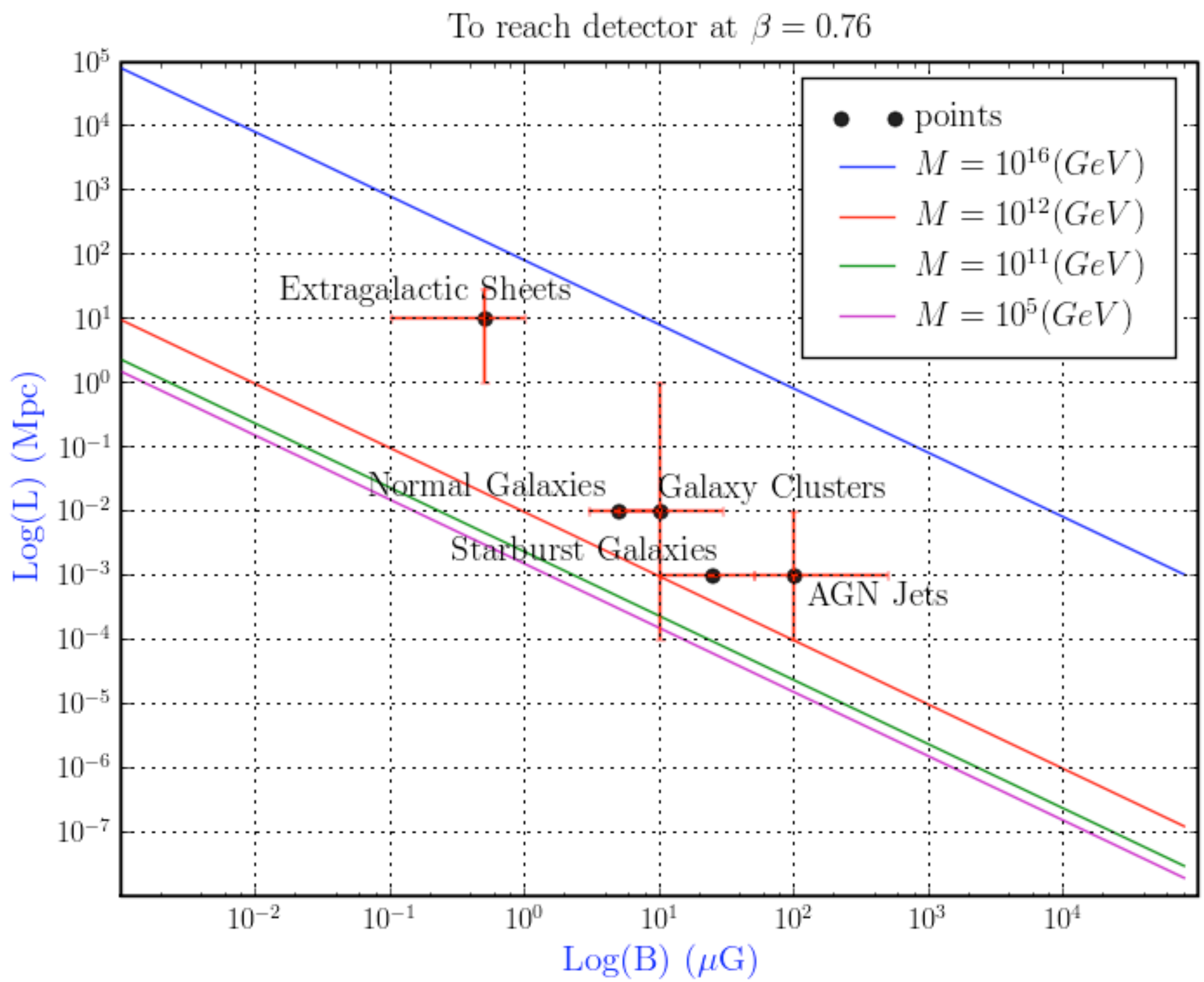


•Ongoing R&D for a future GZK energy neutrino detector focuses on radio Askaryan and acoustic detection.

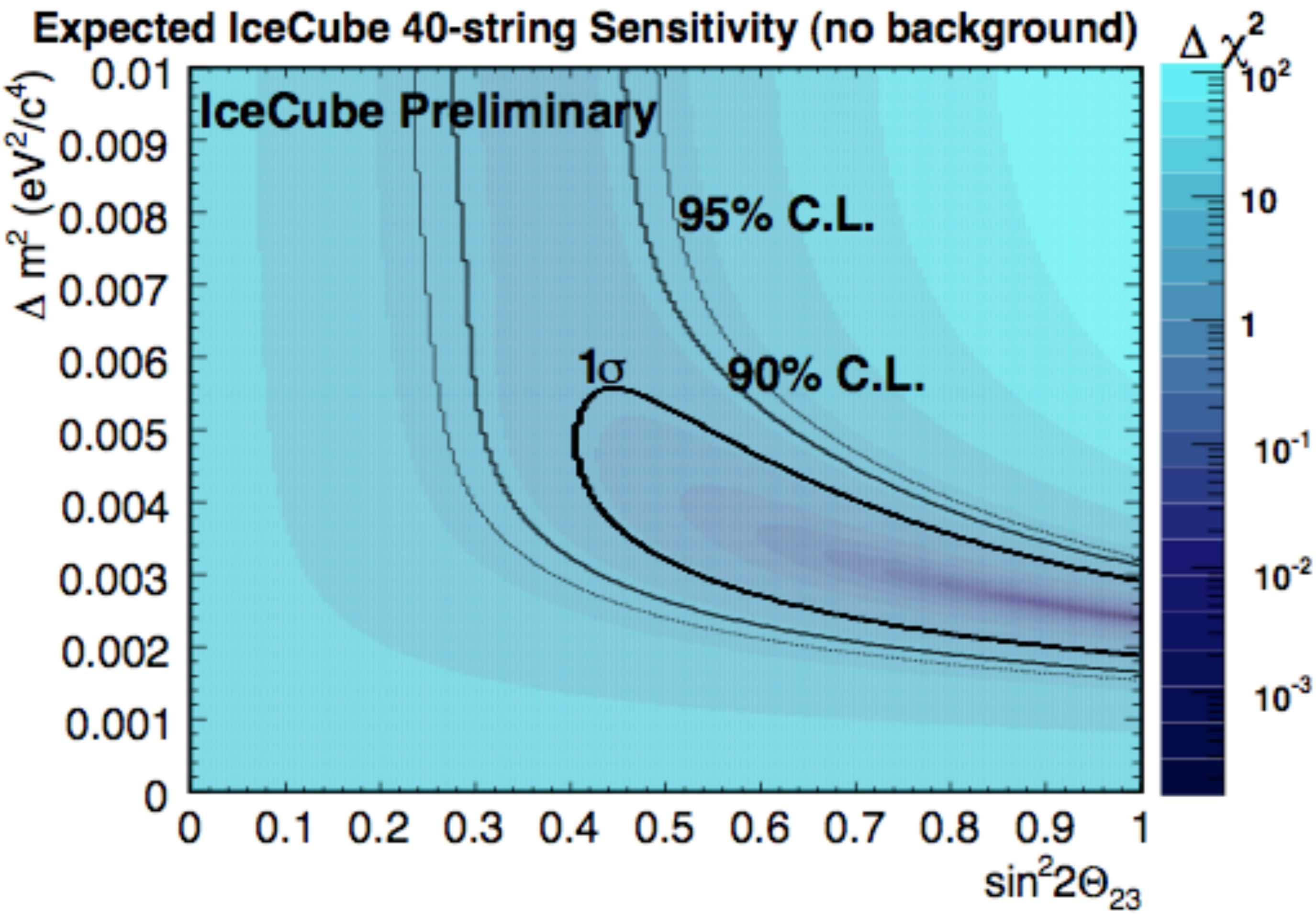


•Propagation of sound and RF in cold ice are being studied using in situ measurements.

•Optimal technologies and array configurations under investigation.



To reach detector at $\beta = 0.76$
points
$M = 10^{16}(GeV)$
$M = 10^{12}(GeV)$
$M = 10^{11}(GeV)$
$M = 10^{5}(GeV)$
Extragalactic Sheets
Normal Galaxies
Galaxy Clusters
Starburst Galaxies
AGN Jets
Log(L) (Mpc)
Log(B) (μG)



Expected IceCube 40-string Sensitivity (no background)
IceCube Preliminary
95% C.L.
90% C.L.
1σ
Δ m² (eV²/c⁴)
sin²2Θ₂₃
Δ χ²
0.01
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
10²
10
1
10⁻¹
10⁻²
10⁻³