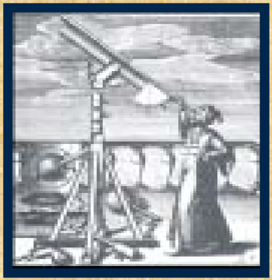


Quick Review of HE Neutrino Detectors

Neutrino Physics is Blossoming, Neutrino Telescopes are Coming into Reality and New Techniques are Pioneered.

We are about to begin regular neutrino astronomy!

John Learned at ASHRA Meeting in Hawaii, 8 January 2004

Outline

- Projects, old and new:
  - Underground (SK, Soudan, INO, HyperK, UNO….)
  - Underwater and Ice (ANTARES, AMANDA, Baikal, Icecube, NEMO,NESTOR)
  - Radio from the Moon and Earth (GLUE, RICE, ANITA, SALSA)
  - Hearing Neutrinos (AUTEC, SADCO)
  - GZK EAS Projects are ν detectors too (AGASA, HiRes, AUGER, EUSO, OWL, ASHRA)

And this in not even mentioning the explosion in neutrino experiments at or associated with accelerators (K2K, Minos, MiniBOONE, ICARUS, JHF …) and at lower energies (KamLAND, SNO, GNO, Gallex,….)

For review see J. Learned and K. Mannheim, Ann. Rev. Nucl. Part. Sci. 2000, 50:679-749

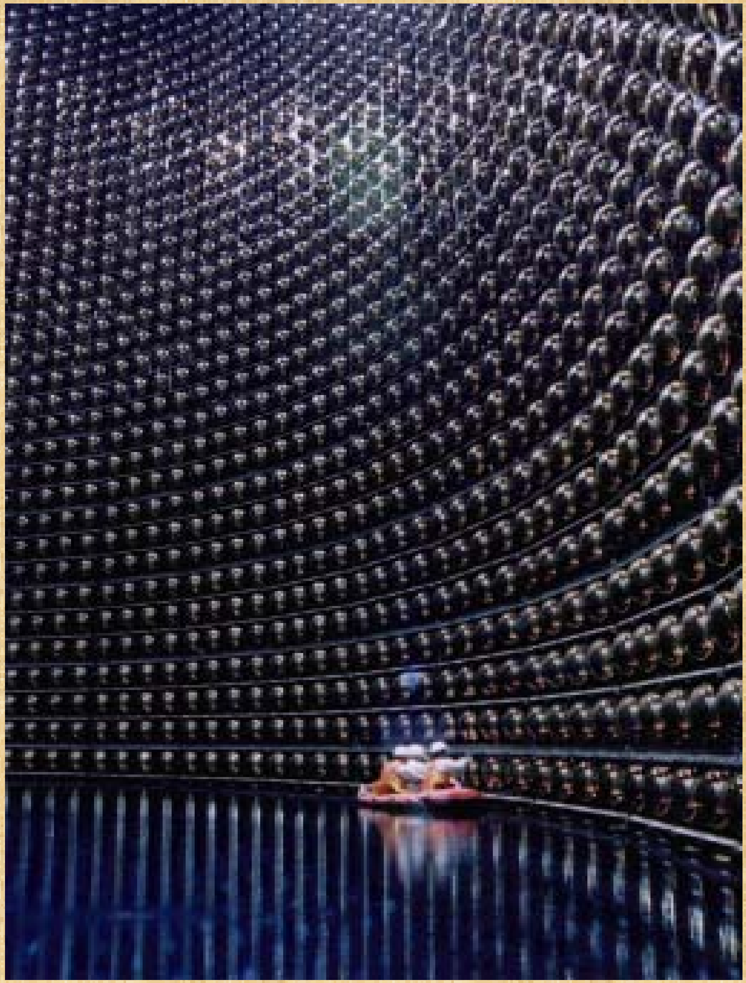
Super-Kamiokande

Biggest Current Underground ν Detector

rebuilt in 2002 to ½ density of PMTs

- Since Apr. '96, >1400 days
- 22,500 ton fiducial Vol.
- 1,200 m^2 muon area
- 4 MeV – 200 GeV evts
- ~20,000 Solar ν's
- >11,000 FC atm ν's
- >2000 upcoming μ's
- Strong evidence for

  $\nu_\mu \leftrightarrow \nu_\tau$ oscillations
  - also from K2K, Soudan & MACRO



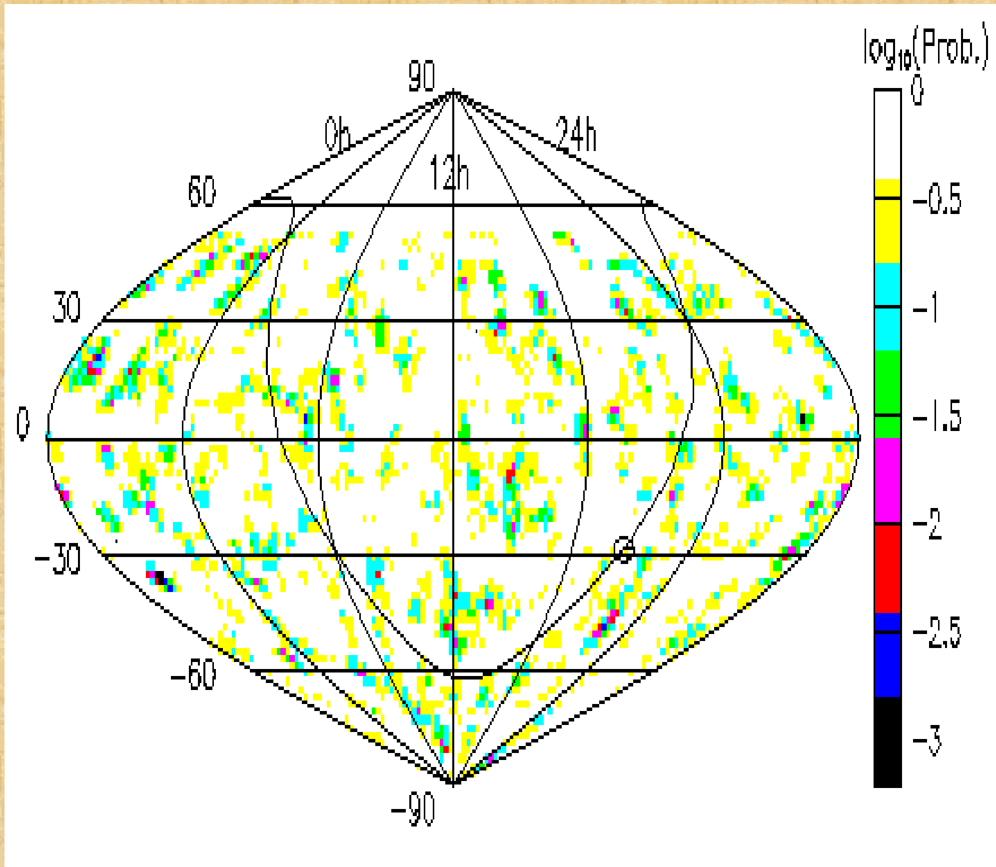
ICRR, U-Tokyo

SuperK Upcoming Muon Cosmic ν Limits

E_μ>1.4 GeV: <E_ν>~100 GeV

But Sadly no Signals Yet

Preliminary



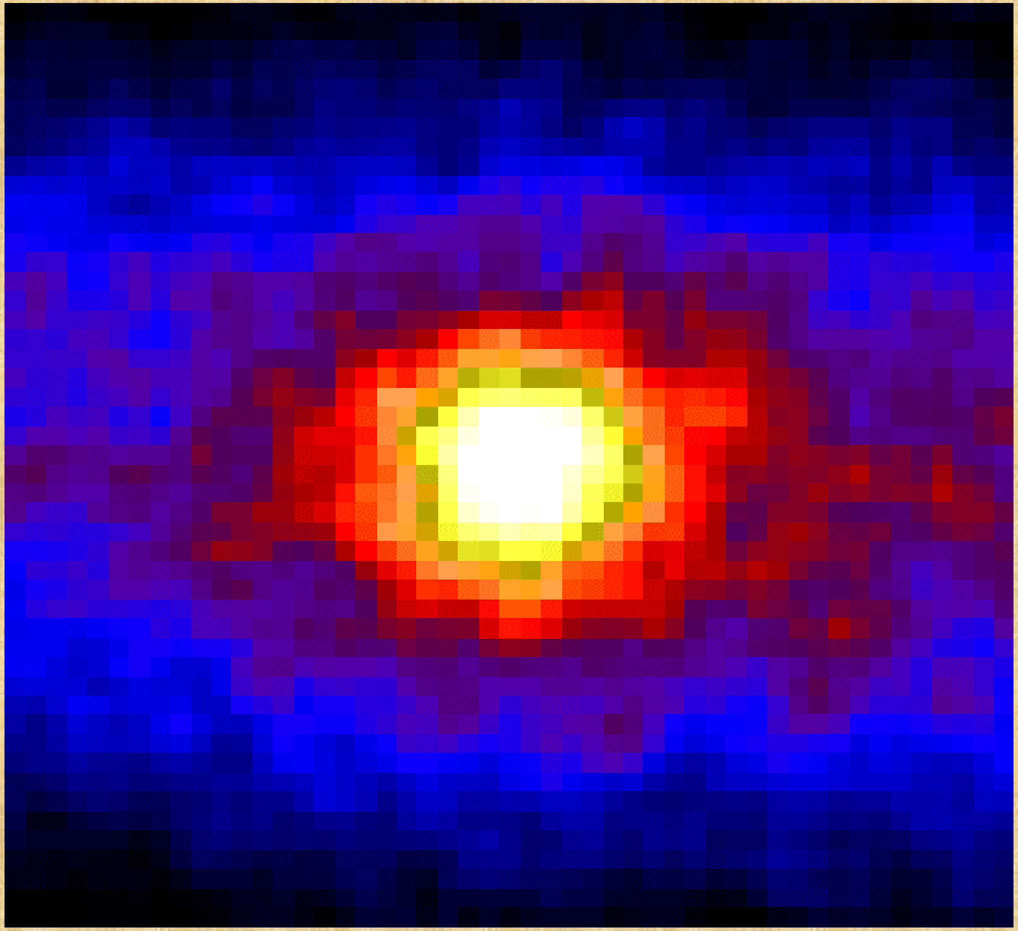
Source name	upmu observed (in 4° cone)	noise expected	Accept. (cm^2)	Flux Limit ($cm^{-2} s^{-1}$)
Cyg X−1	6	2.0	4.1×10^6	2.4×10^{-14}
Cyg X−3	1	1.8	3.5×10^6	1.03×10^{-14}
Her X−1	1	1.7	4.1×10^6	8.7×10^{-15}
Sco X−1	2	2.6	6.9×10^6	7.0×10^{-15}
Vela X−1	5	2.9	8.6×10^6	9.9×10^{-15}
Crab N.	0	1.8	5.1×10^6	4.1×10^{-15}
3C273	6	2.4	6.2×10^6	1.6×10^{-14}
Per A	1	1.9	3.4×10^6	1.05×10^{-14}
Vir A	1	1.7	5.7×10^6	6.3×10^{-15}
Coma cl.	2	1.7	4.7×10^6	1.03×10^{-14}
Gemminga	3	2.0	5.4×10^6	1.14×10^{-14}
G.C.	3	2.2	7.6×10^6	8.0×10^{-15}
Mrk 421	2	1.9	3.8×10^6	1.28×10^{-14}
Mrk 501	1	1.9	3.6×10^6	9.9×10^{-15}

others from CWRU, KGF, Baksan, Frejus, IMB, Kam, Baikal, MACRO, AMANDA....

Matsuno, UH

But Neutrino Astronomy Began with Solar Neutrinos 30 Yrs Ago!

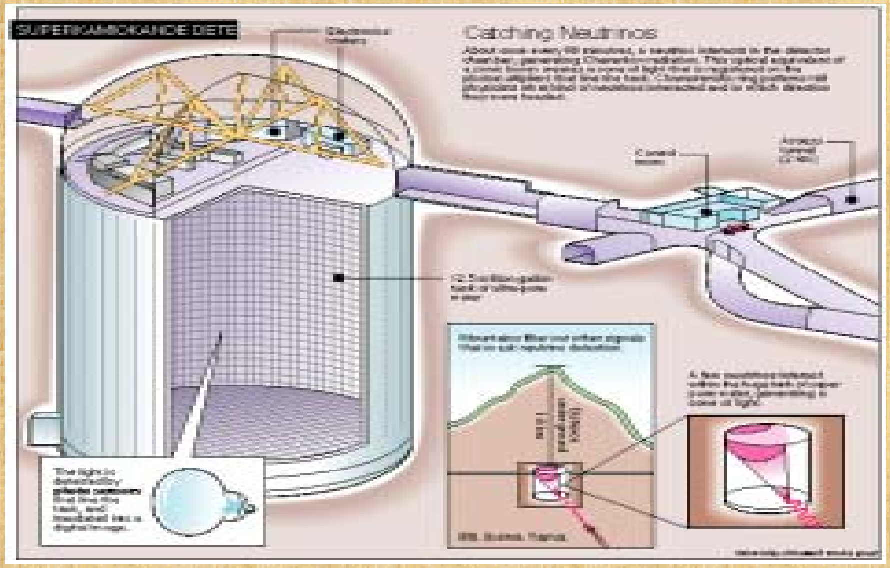
- SK Portrait of the Sun in Neutrinos
- Data from Homestake, SAGE, GALLEX/GNO, Kamioka, SuperK, SNO
- But Flux Only ~1/2-1/3 of Expectations

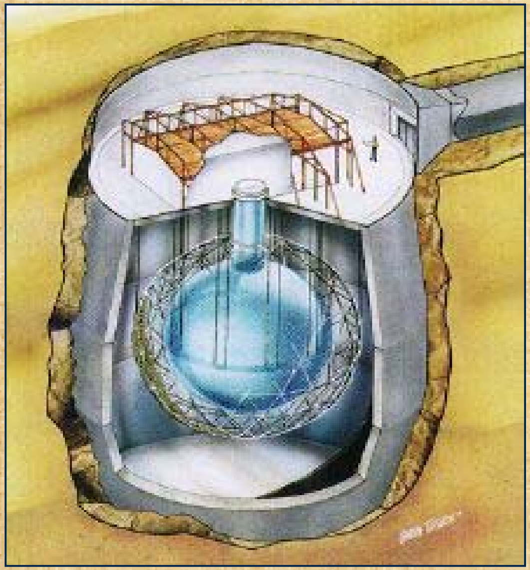


R. Svoboda, LSU

ν

SuperK – SNO
Solar ν Neutrino Results

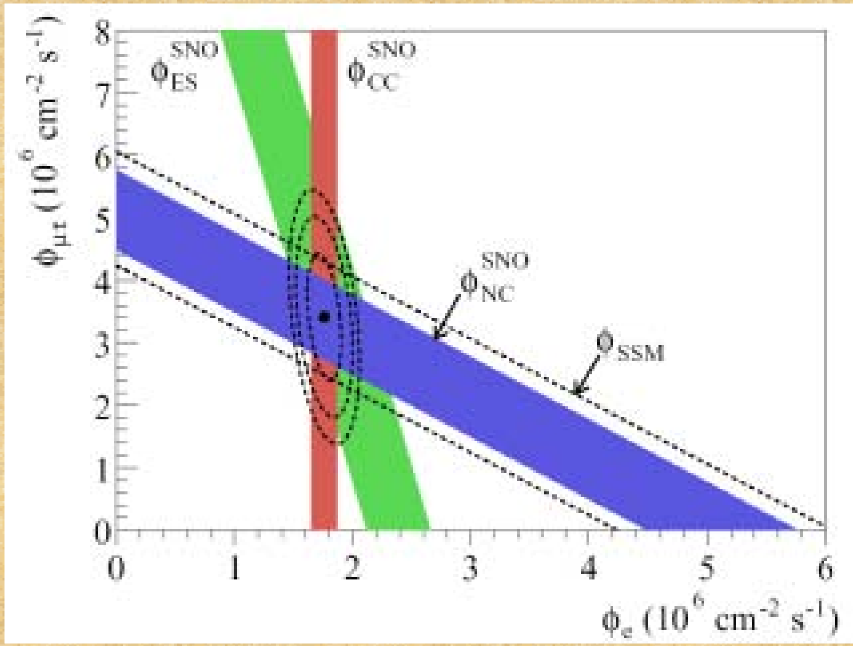


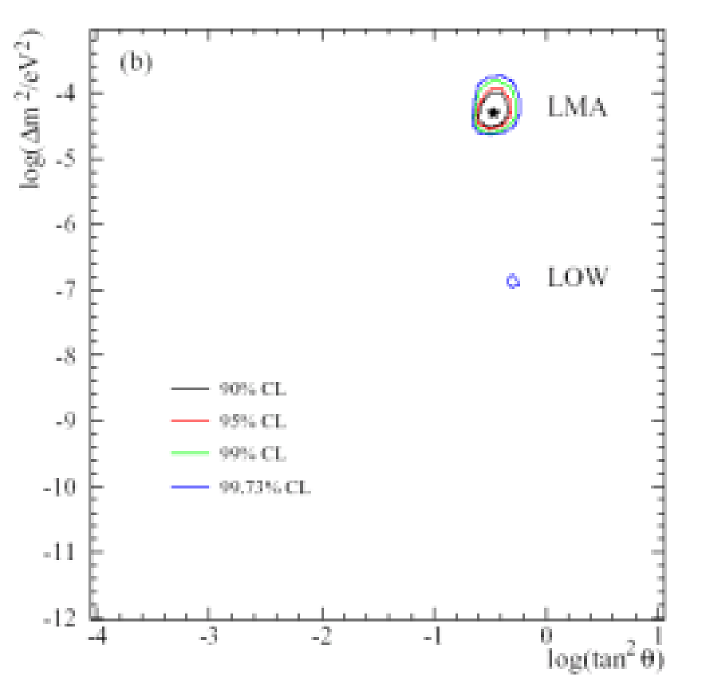


- [SK elastic +SNO CC&NC] **=> ν_e Oscillations**
- With new SK & SNO Data ('02), **almost sure**.
- **Solar ν astronomy yields fundamental physics**

SNO + SK + Ga + Cl Data Imply Oscillations, Probably LMA

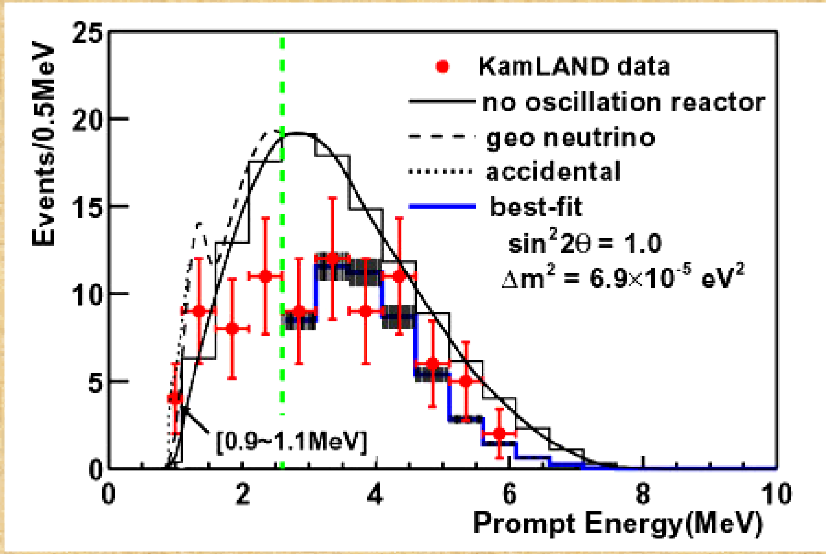
- Beautiful SNO (4/02) ES, NC & CC Data

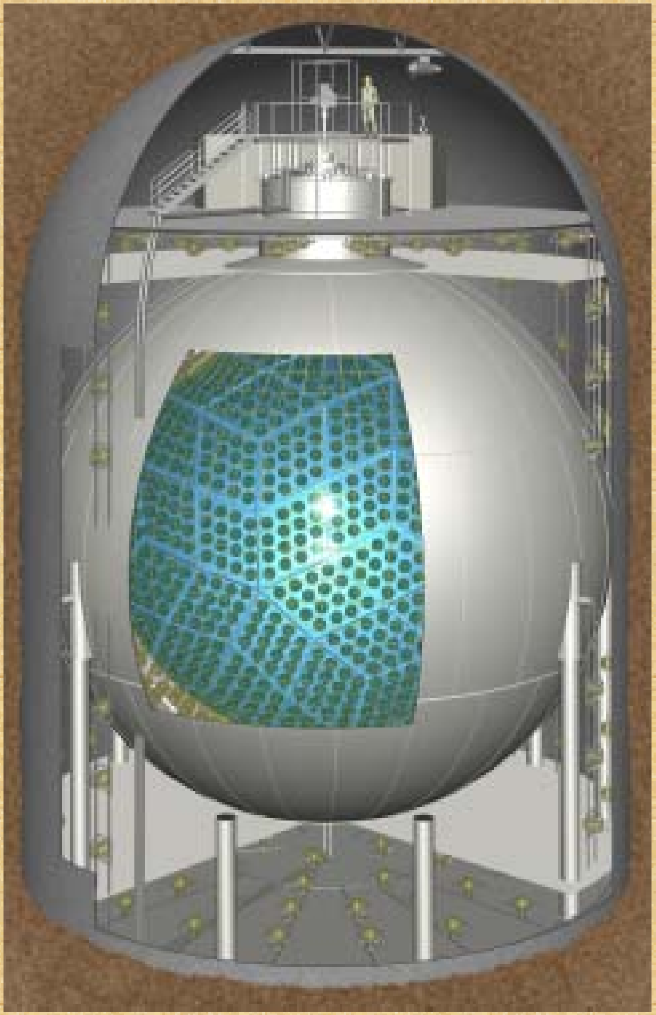




KamLAND
taking data, first results 12/02

- Measure ν_e's from reactors in Japan at ~175 km distance.
- Makes ***terrestrial*** measurement.





KamLAND First Results

Final sample 54 events

($E_{prompt} > 2.6$ MeV)

Predicted 86.8 ± 5.6 events
(no osc)

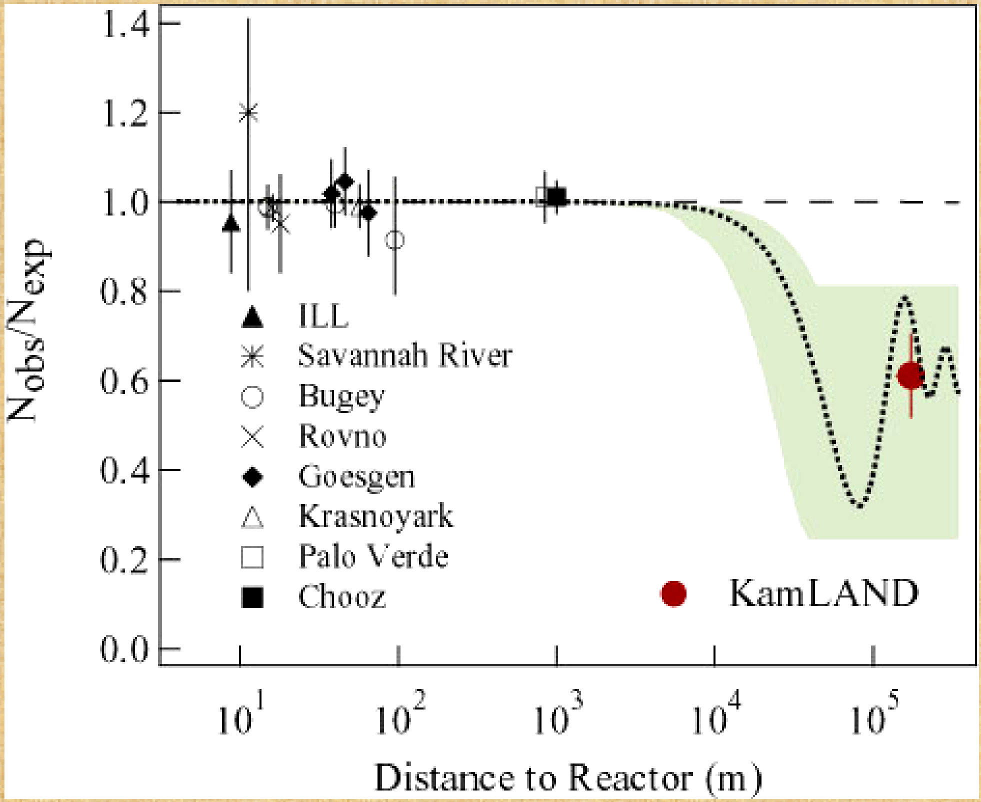
Background 0.95 ± 0.99 events

accidental 0.0086 ± 0.0005

9Li/8He 0.94 ± 0.85

fast neutron < 0.5

$(N_{obs} - N_{bgd})/N_{pred}$ = 0.611 ± 0.085 (stat) ± 0.041 (syst)



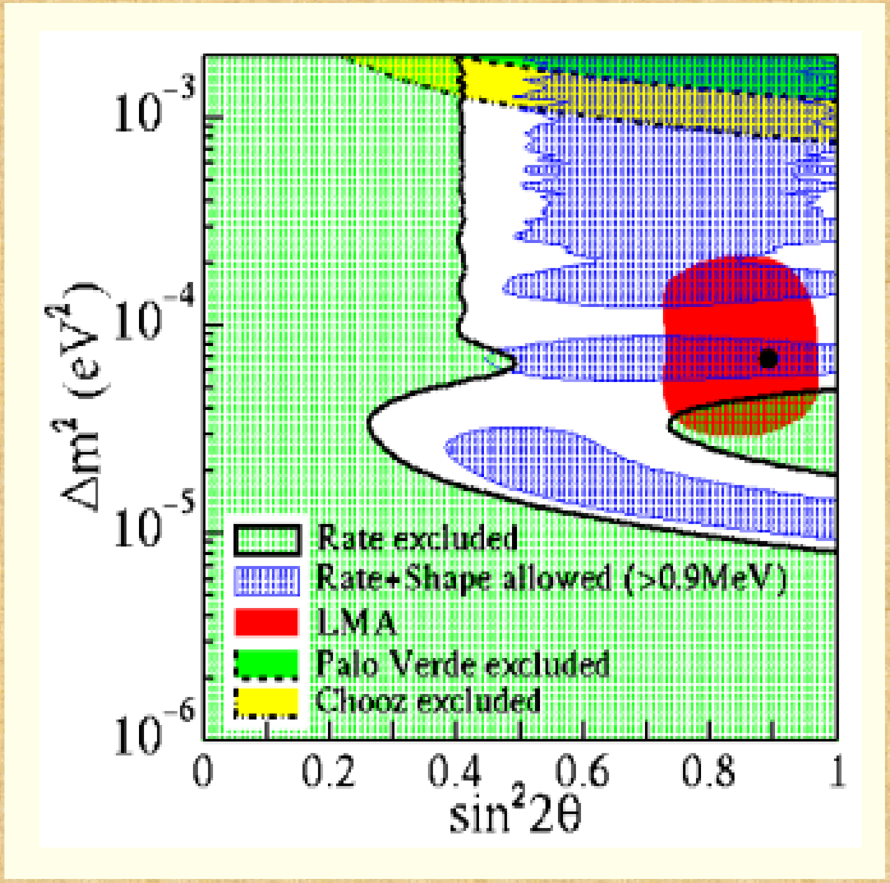
KamLAND + Solar Results: Almost Certainly LMA Oscillations

ν

Oscillations Best fit :

$DM^2 = 6.9\text{x}10^{-5}eV^2$

$sin^2\ 2\ q = 0.91$



Fitted $\bar{\nu}_{geo}$ events:

4 for ^{238}U

5 for ^{232}Th

0 ~ 110 TW at 95 % C.L.

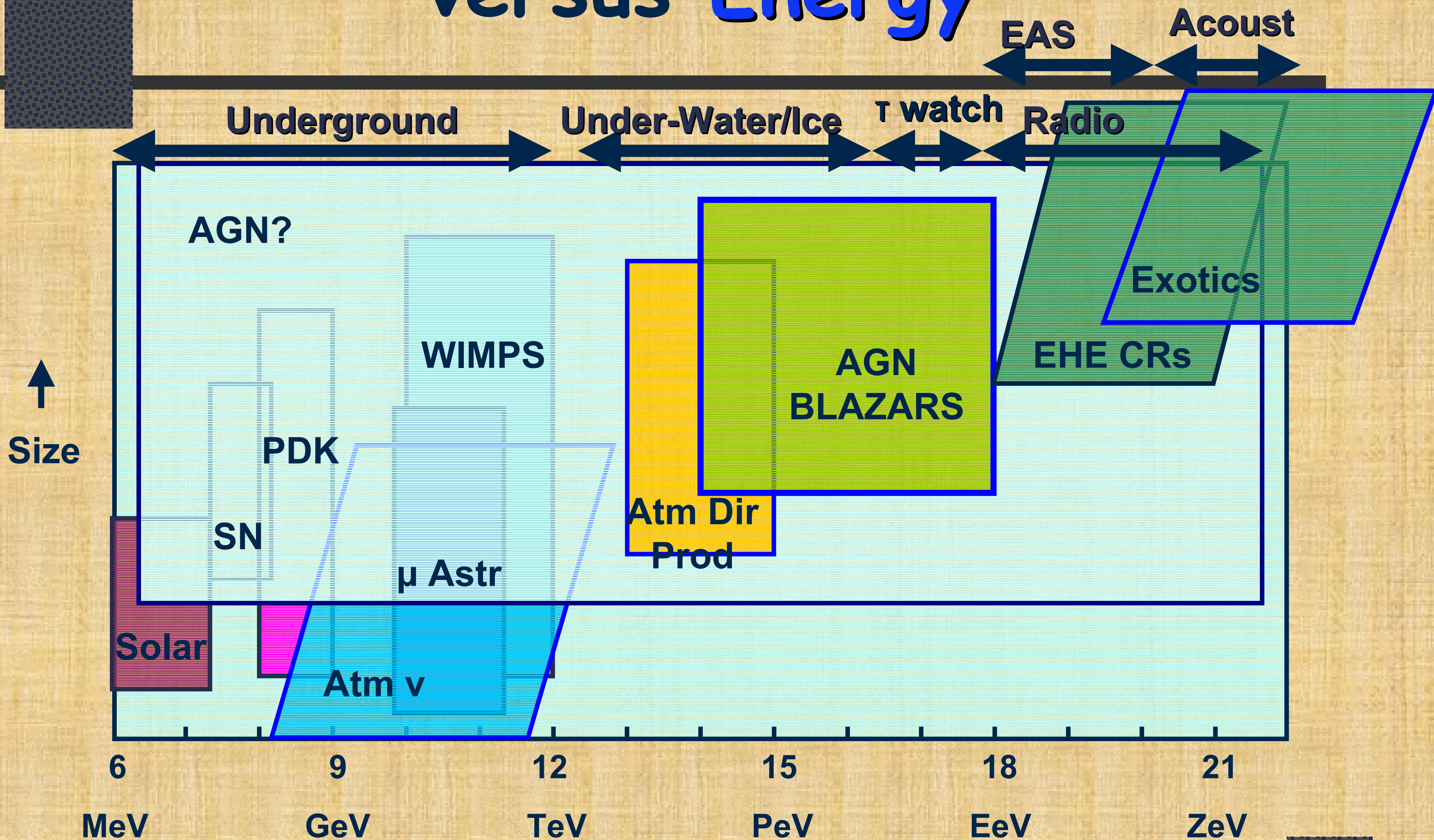
ν

Neutrino "Astronomy" Accomplishments Summary

- Supernovae: 1 seen (SN1987A) and waiting.
- Cosmic Ray ν's: ν_μ oscillations, parameters and model constraints tightening.
- Solar Neutrinos: oscillations, nearly settled?
- Cosmic ν limits: from non-dedicated detectors (CWRU, Kolar, Baksan, IMB, Kam, Frejus, NUSEX, LSD, LVD, MACRO…).
- Limits on WIMPs, monopoles, GRB ν's, …
- First very large, dedicated, high energy ν telescopes now building.

Physics and Techniques versus Energy

ν

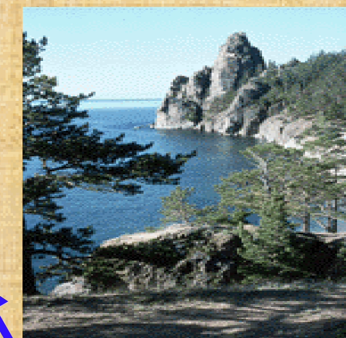


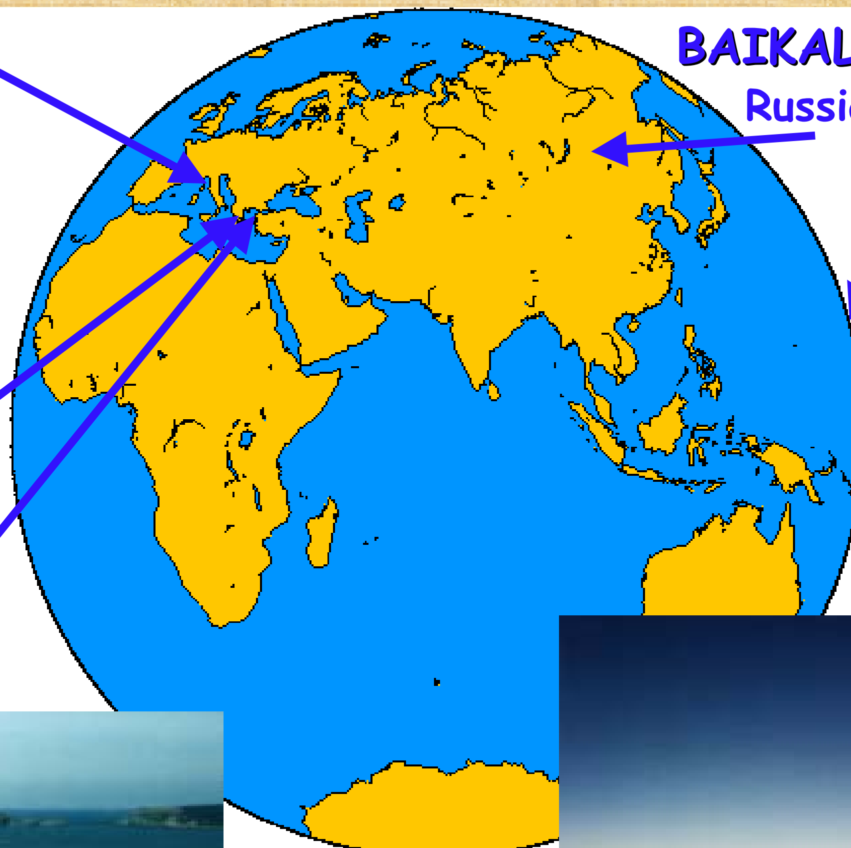
V

Optical Cherenkov
Neutrino Telescope Projects

ANTARES
La-Seyne-sur-Mer, France

BAIKAL
Russia

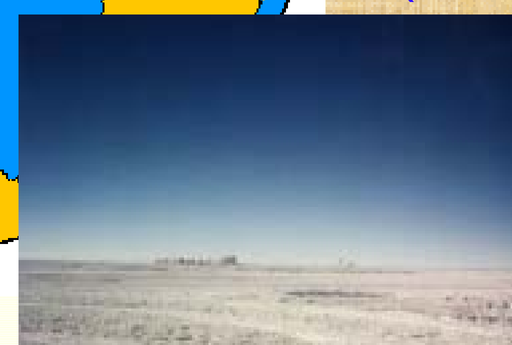




NEMO
Catania, Italy

DUMAND
Hawaii
(cancelled 1995)

NESTOR
Pylos, Greece



AMANDA/ ICECUBE,
South Pole, Antarctica

V

Water versus Ice

Deployment

Ice gives solid platform to install detector

Sea experiments need boats/ platforms

Ice detectors worked first (Baikal deploys from ice)

Angular Resolution

Light scattering much less in water

AMANDA : ~ 3° (real detector)

ANTARES : ~ 0.4 ° (simulations)

Uniformity of Detector response

Water homogeneous

Ice has dust layers, bubbles

Knowledge of efficiency simpler in water

Noise Backgrounds

Water: ^{40}K /bioluminescence ~ 60kHz / PMT

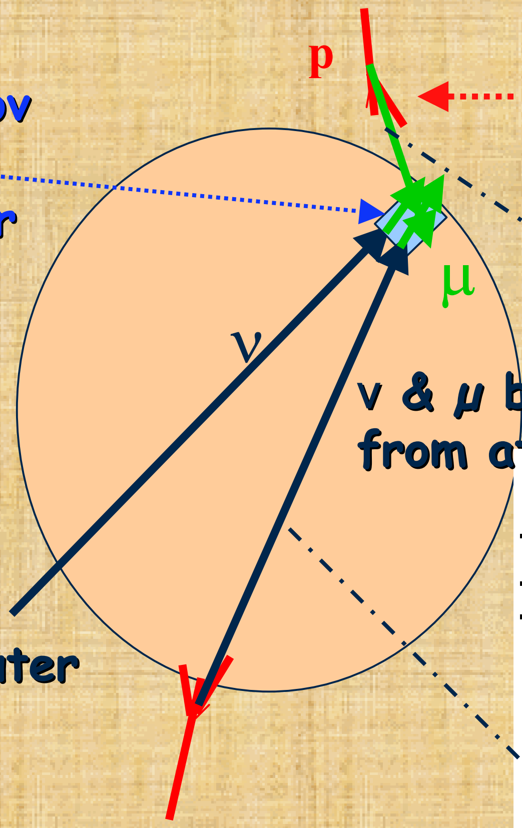
Ice: only dark tube noise ~ 5kHz / PMT

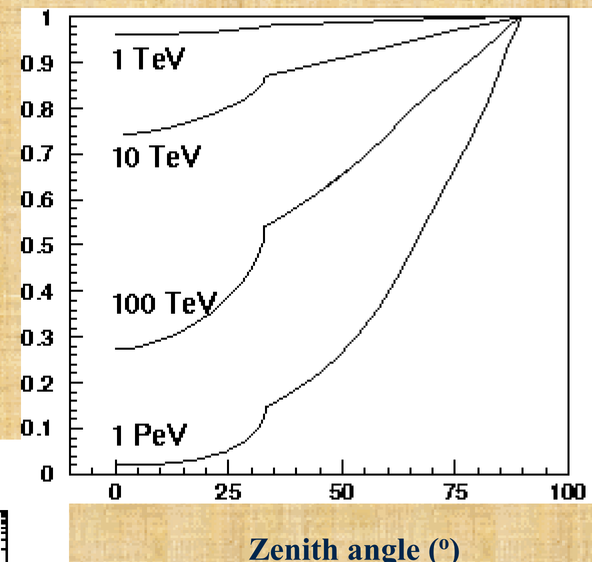
Detector design must take into account

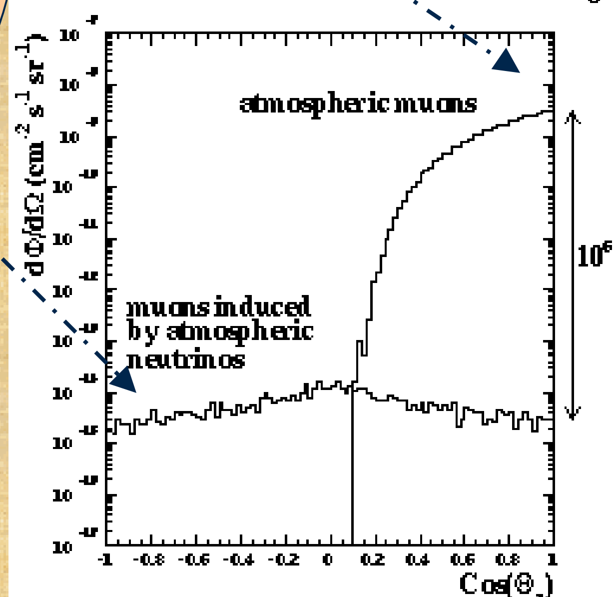
J. Carr Nu2002

Under Sea, Lake or Ice
Neutrino Telescopes

ν







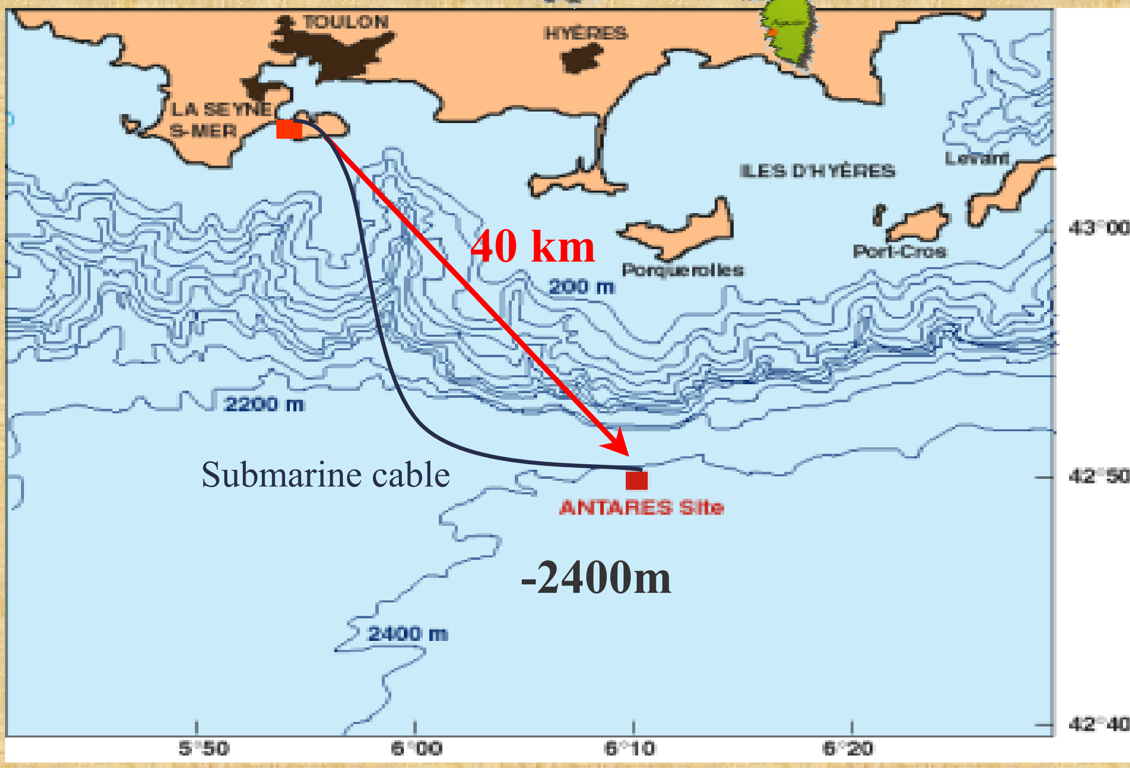
< 1PeV: look for upcoming events
>100 TeV: look for downgoing events

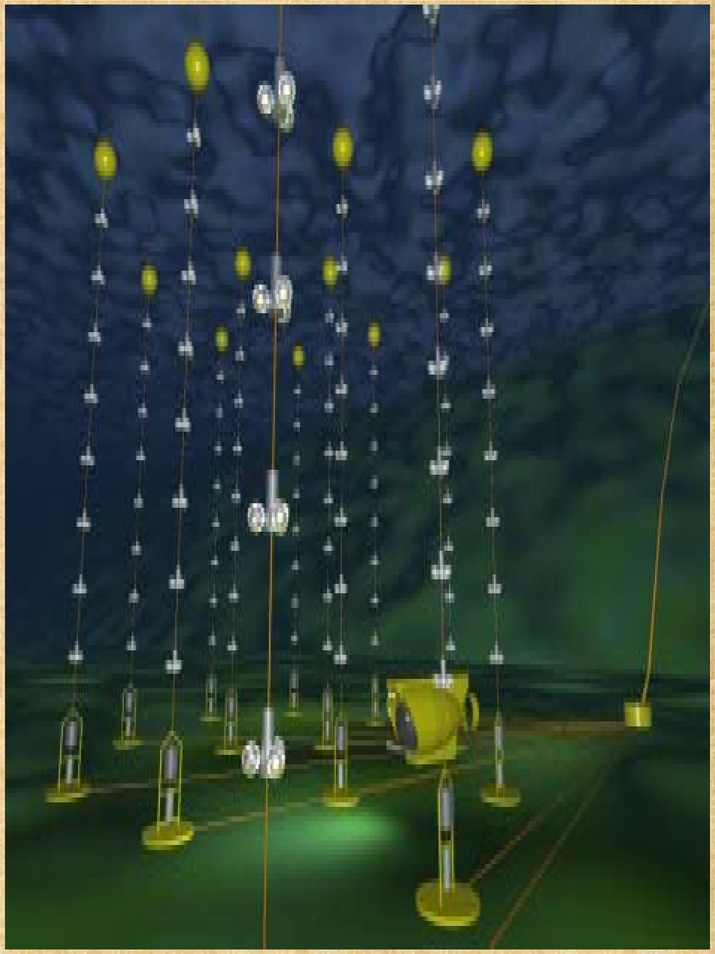
J. Carr

V

ANTARES SITE

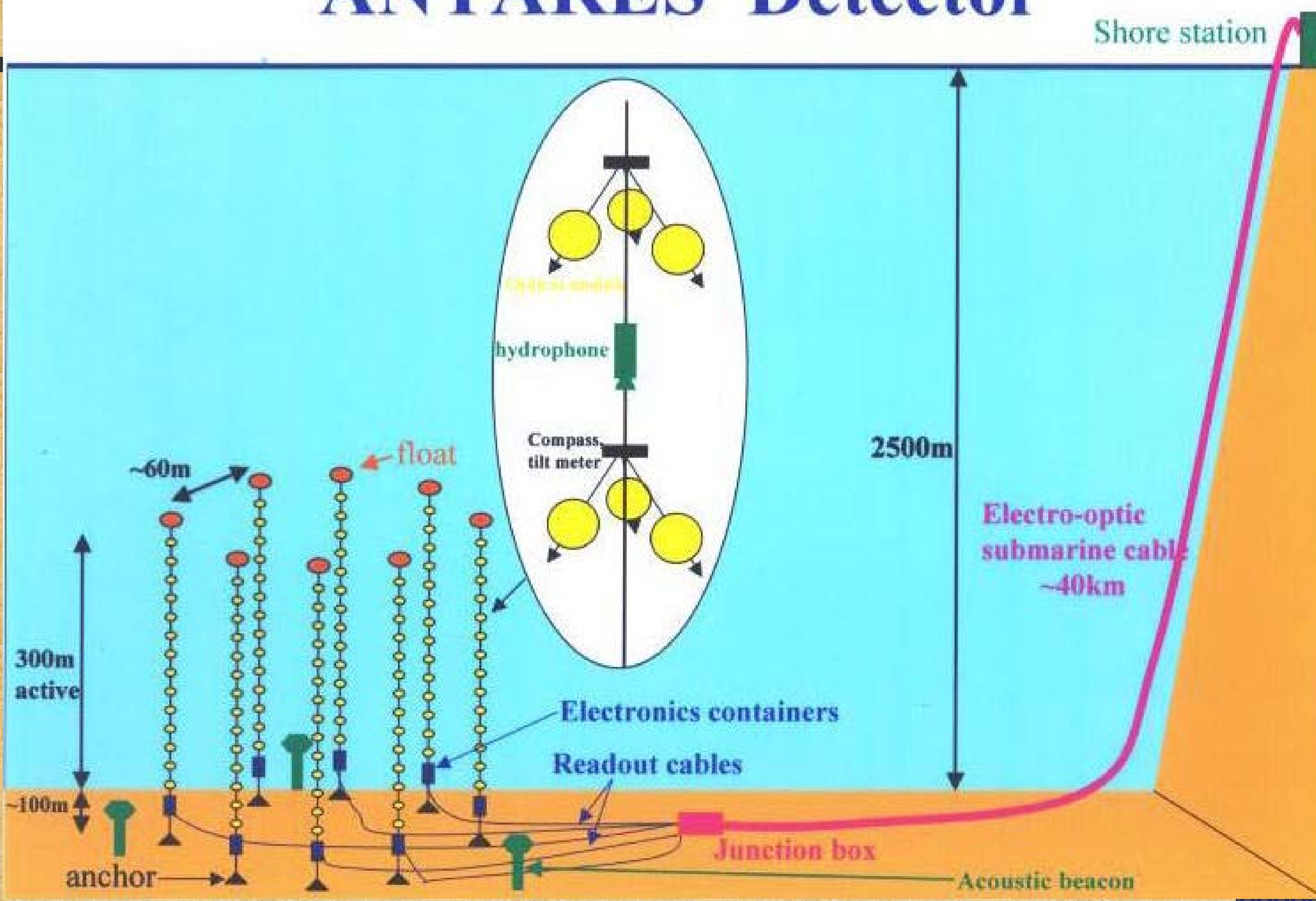
40Km SE Toulon
Depth 2400m
Shore Base
La Seyne-sur-Mer



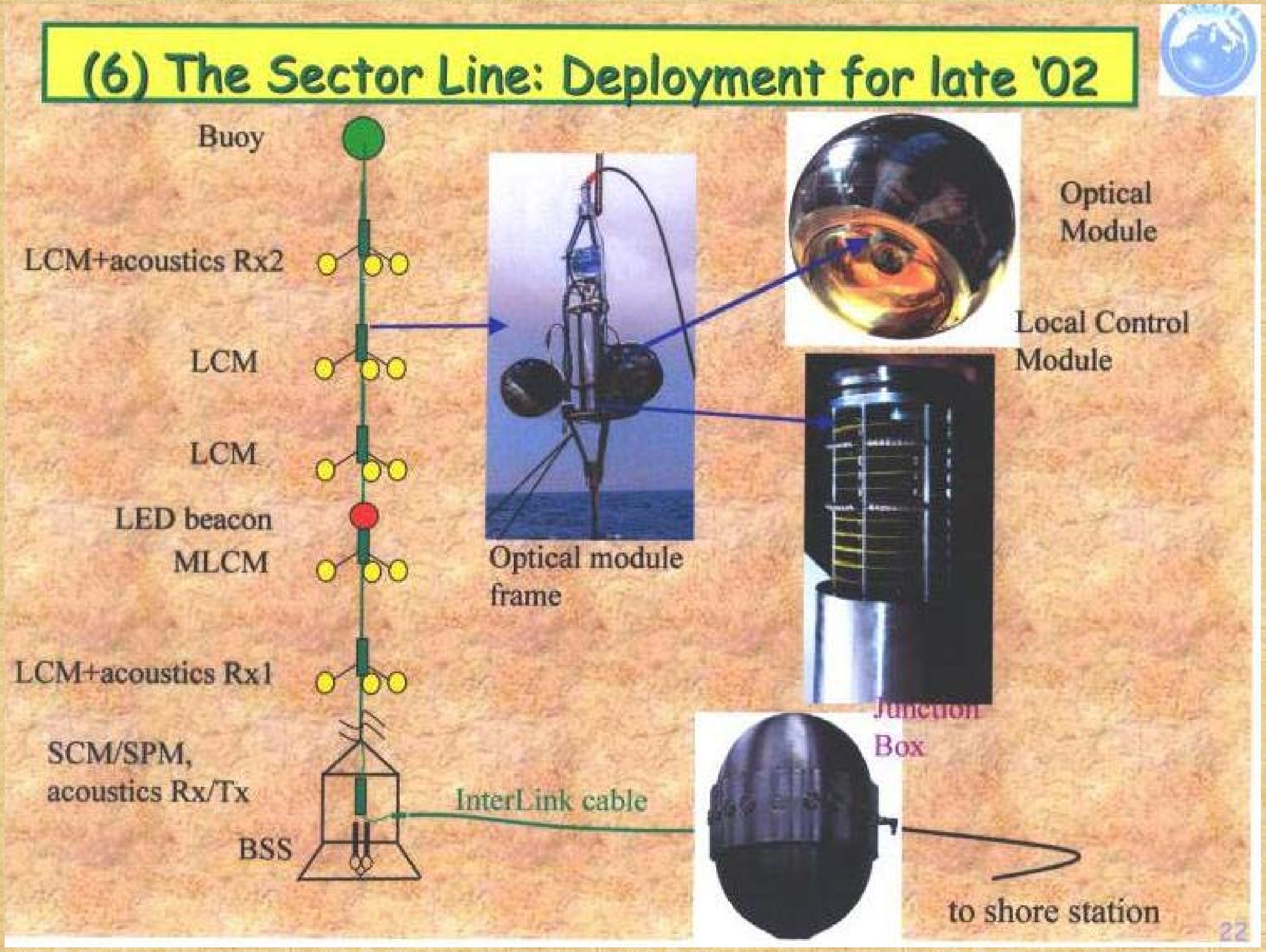


J. Carr

ANTARES Detector



ANTARES Prototype Connected March '03 some problems

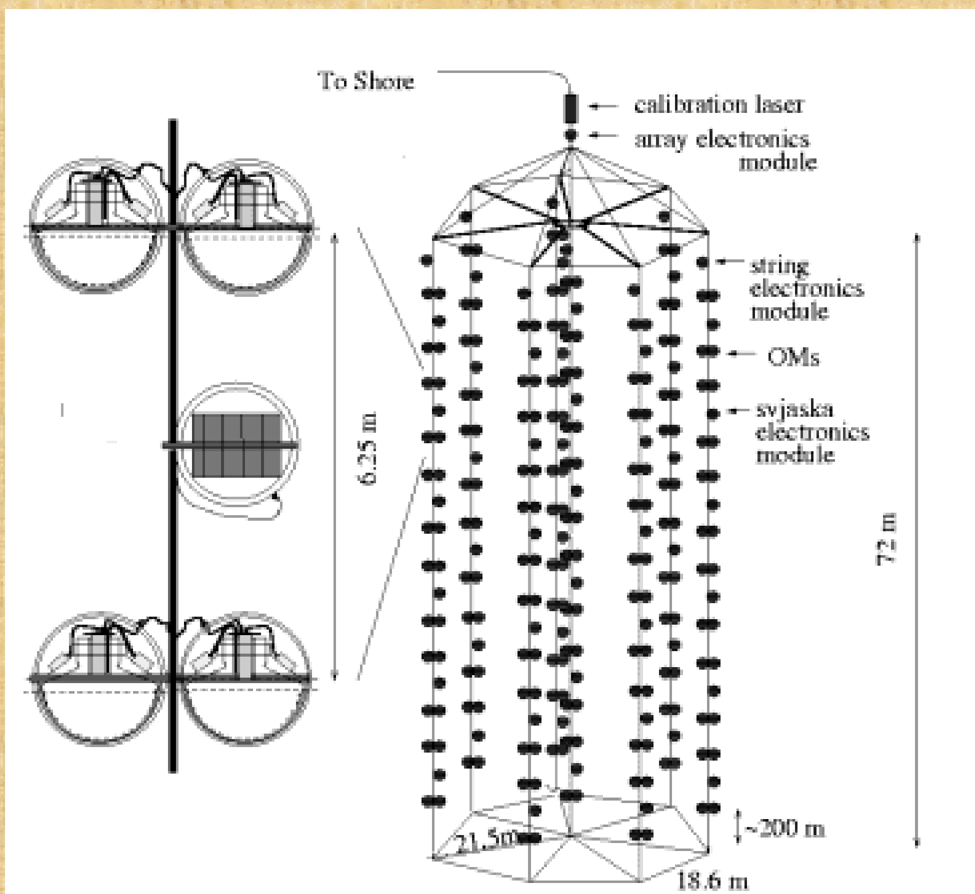


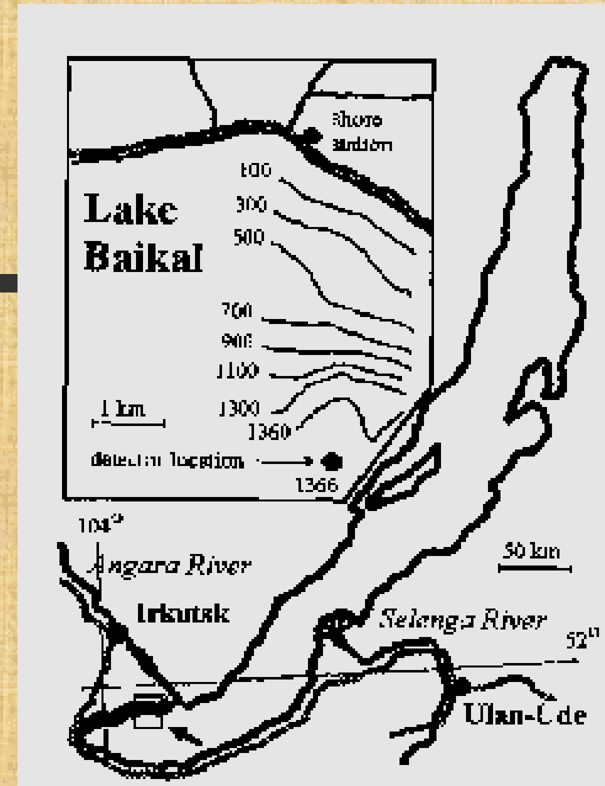
V

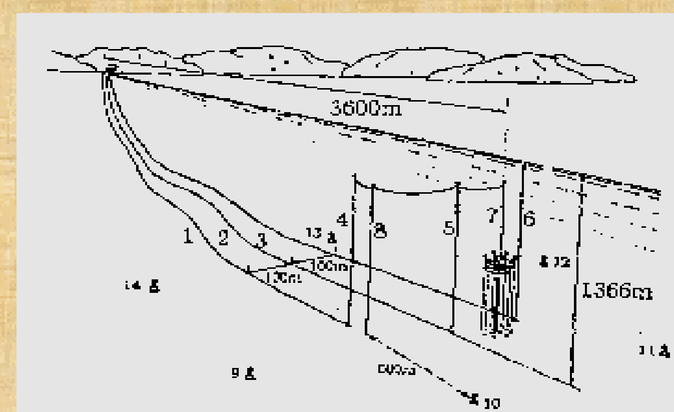
BAIKAL Project

Lake Baikal, Siberia: surface frozen in winter

1993   36 Optical Modules
1998 192 Optical Modules







V

NESTOR

Pylos, Greece

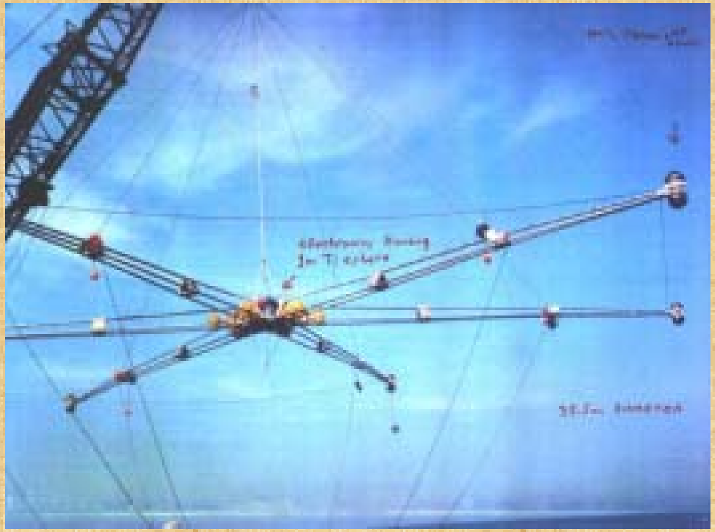
Pylos

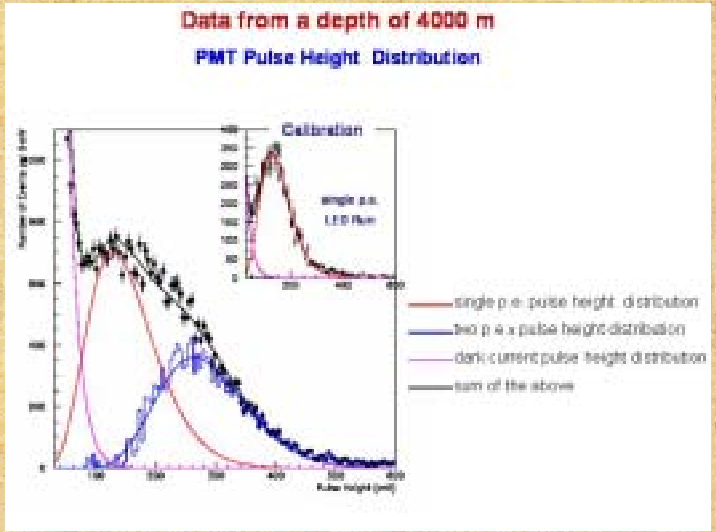
NESTOR Project

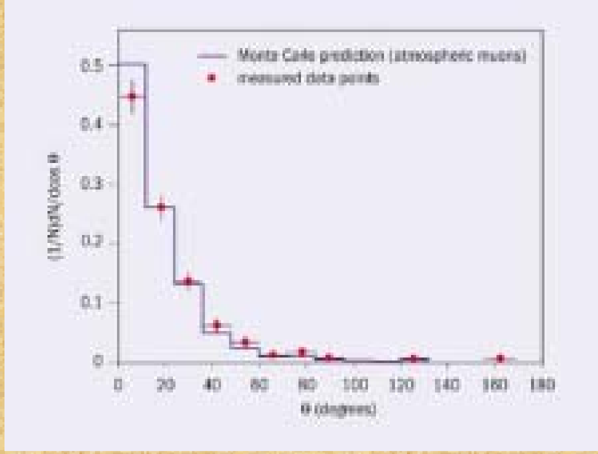
Pylos, Greece 3800m depth

- ~1991 Started
- 1992 Counted Muons
- '92-'01 Many ocean tests, build lab and insfrastructure
- 2000 Lay Cable to site
- 2001 Repair cable,
- 2003 Deploy 1-floor
- 2004 Full tower
- 200? Deployment of 7 NESTOR towers

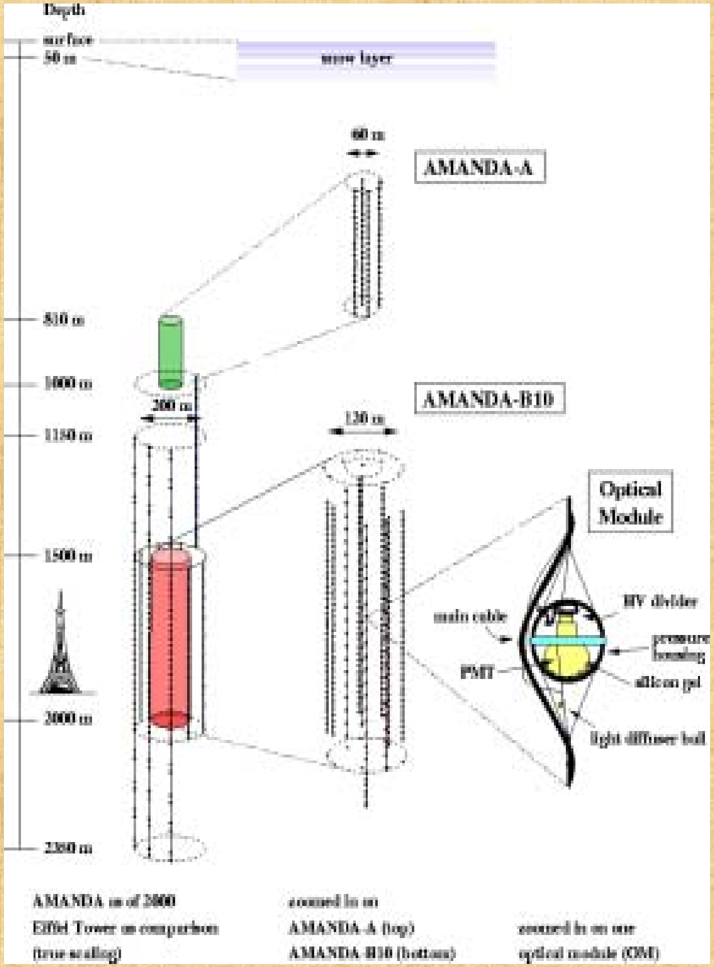
4/03 One NESTOR Floor In Place and Counting







AMANDA
South Pole 2km Deep Ice

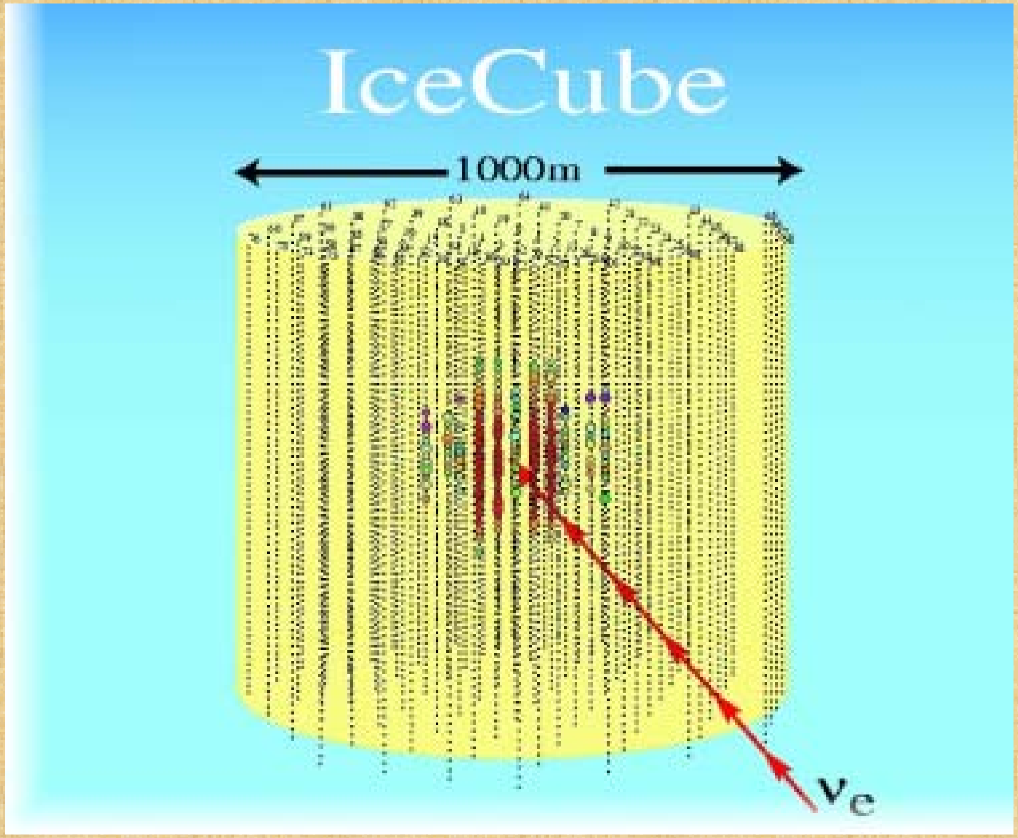


- AMANDA now reporting atmospheric ν_μ data.
- Demonstrated technology.
- Cloudy ice layers hamper analysis, but manageable.

ICECUBE

ν

Perhaps First Km³ Neutrino Detector ~2008

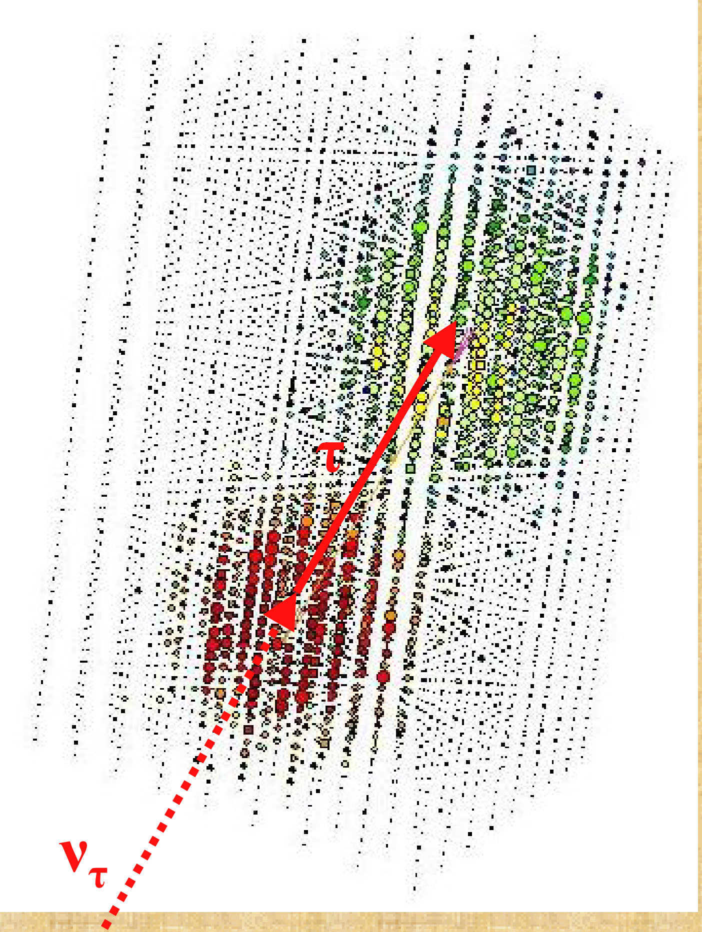


First funds 2002

- 80 strings,
  60 PMT´s each;
  4800 optical modules total
- V ≈ 1 km^3,
  E_{th}~ 0.5-1TeV

ν

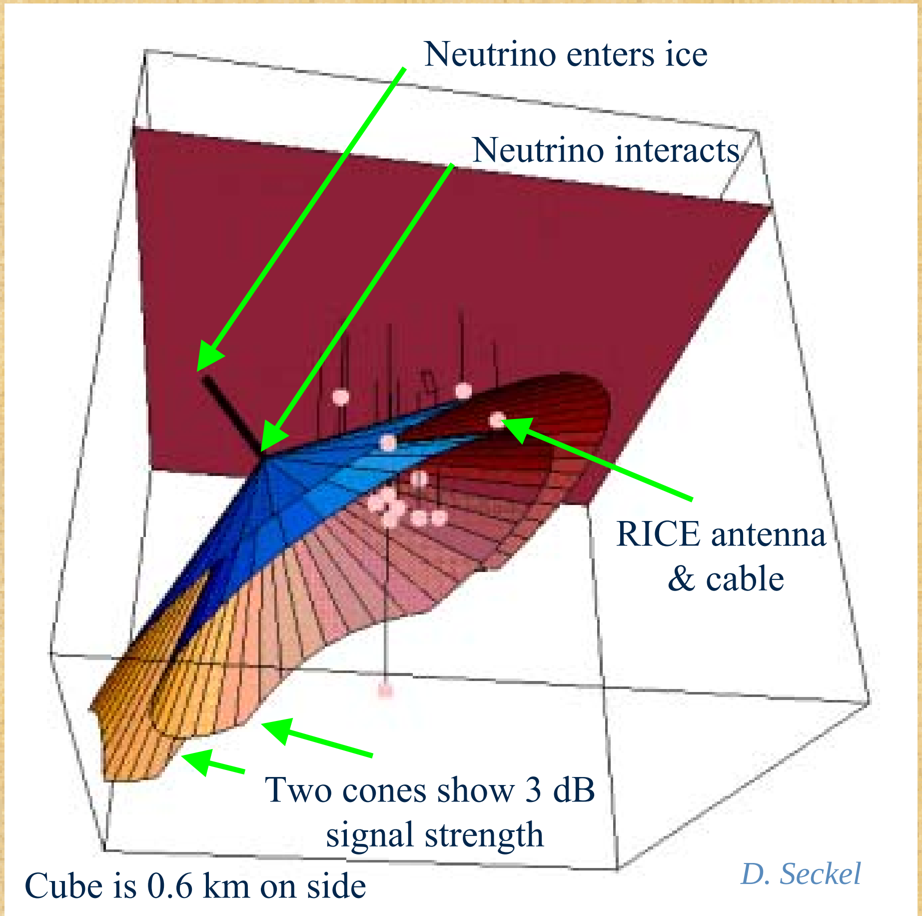
ICECUBE
can see Double Bang events



- Few PeV ν_τ charged current events make unique signature.
- Second splash has ~ twice energy of first.
- Can see lollipops too (single ends of DB).

Possibility to measure flavor mix (with DB + μ's + Glashow events) from pt sources.

RICE
Radio Detection in South Pole Ice

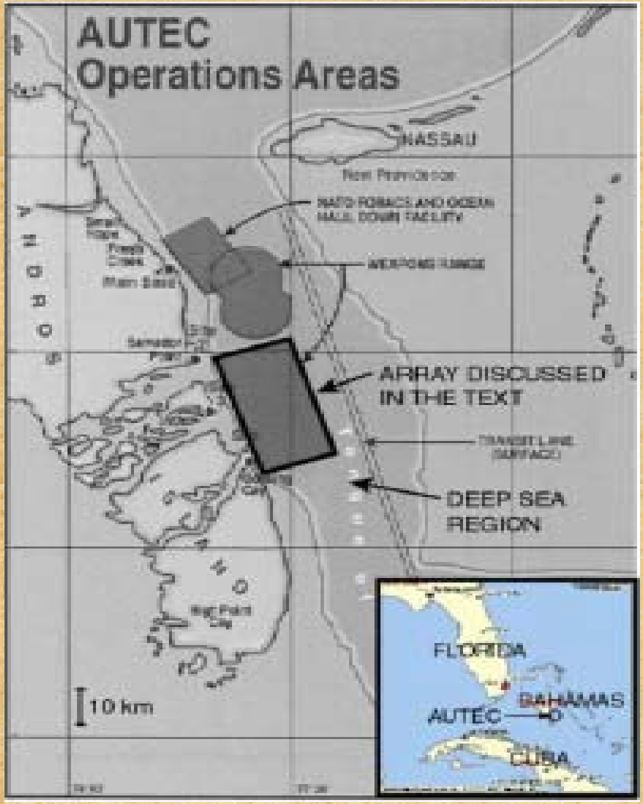


- Installation ~15 antennas few hundred m depth with AMANDA strings (and future ICECUBE strings).
- Tests and data since 1996.
- Most events due to local radio noise, few candidates.
- Continuing to take data, and first limits prepared.

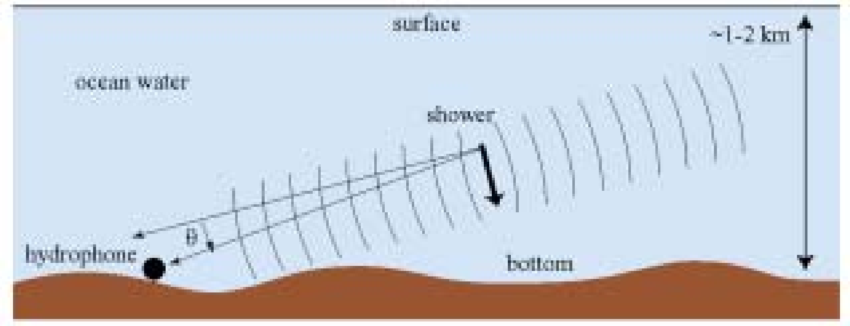
Ocean Acoustic Detection

Renewed efforts for GZK Neutrino Detection in US, Russia and Europe (SADCO)

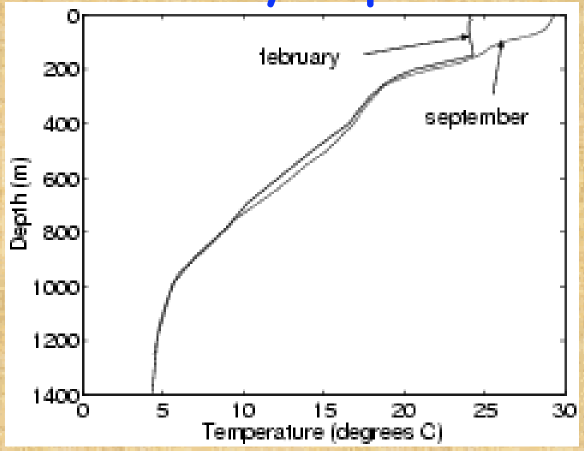
Stanford project to use US Navy array in Atlantic



pancake beam pattern



sound velocity depends on depth



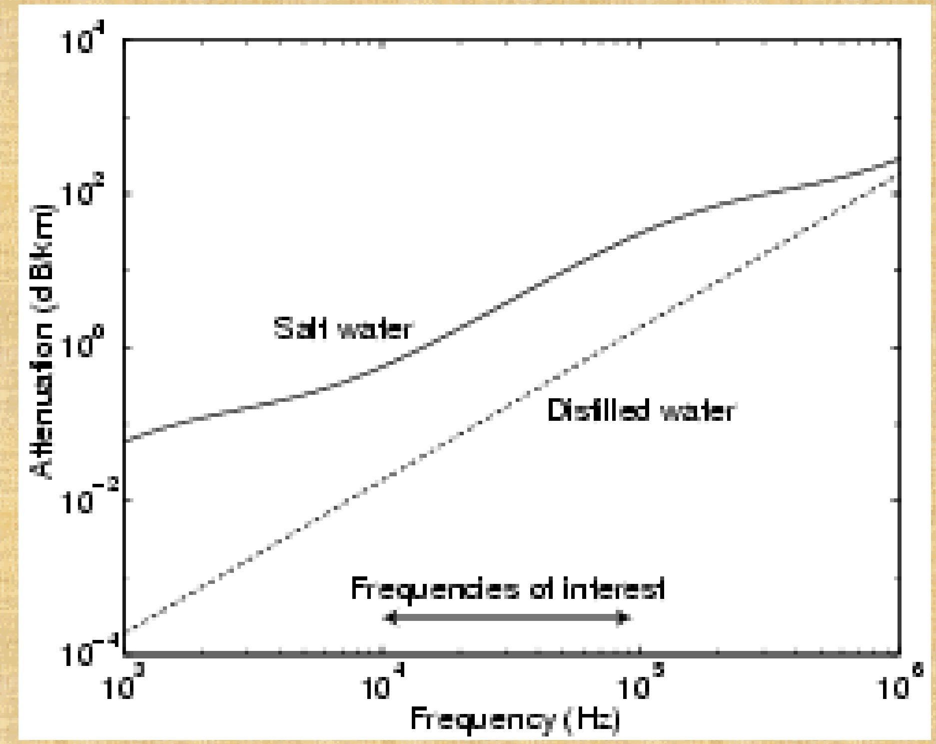
G.Gratta, atro-ph/0104033

ν

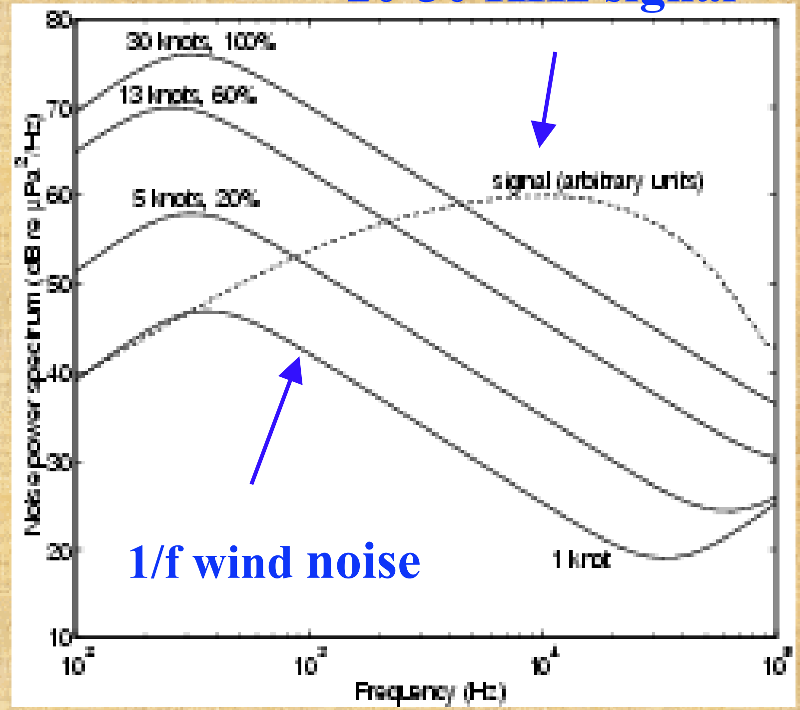
Neutrino Noises are Weak, but 10^{21} eV ν's can be Heard from Afar

Attenuation Length:
Many Km in Ocean

Noise:
Near Deep Ocean Thermal Minimum



~20-30 KHz signal

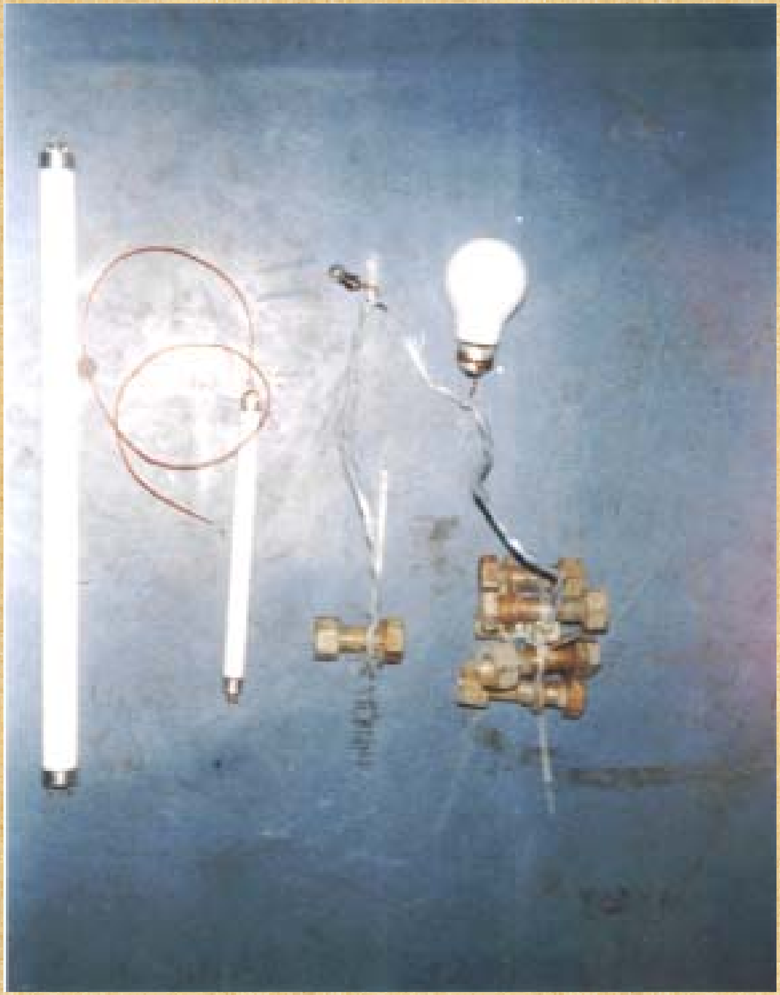


G. Gratta astro-ph/0104033

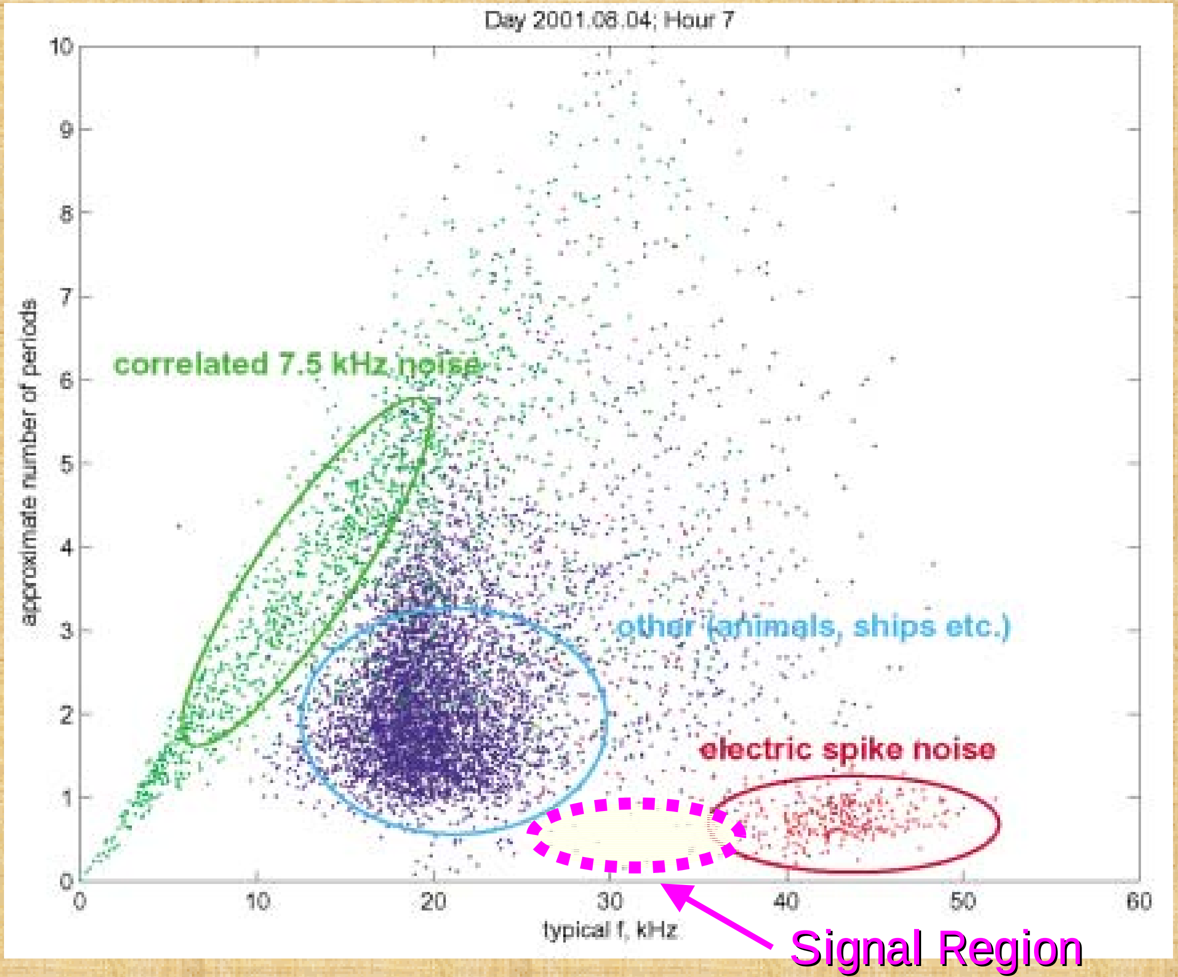
Calibrating Acoustic Detection

Poor man's acoustic calibration sources

They implode at ~100m depth releasing an energy ~ PeV



Stanford Group Has First Background Exploration Data

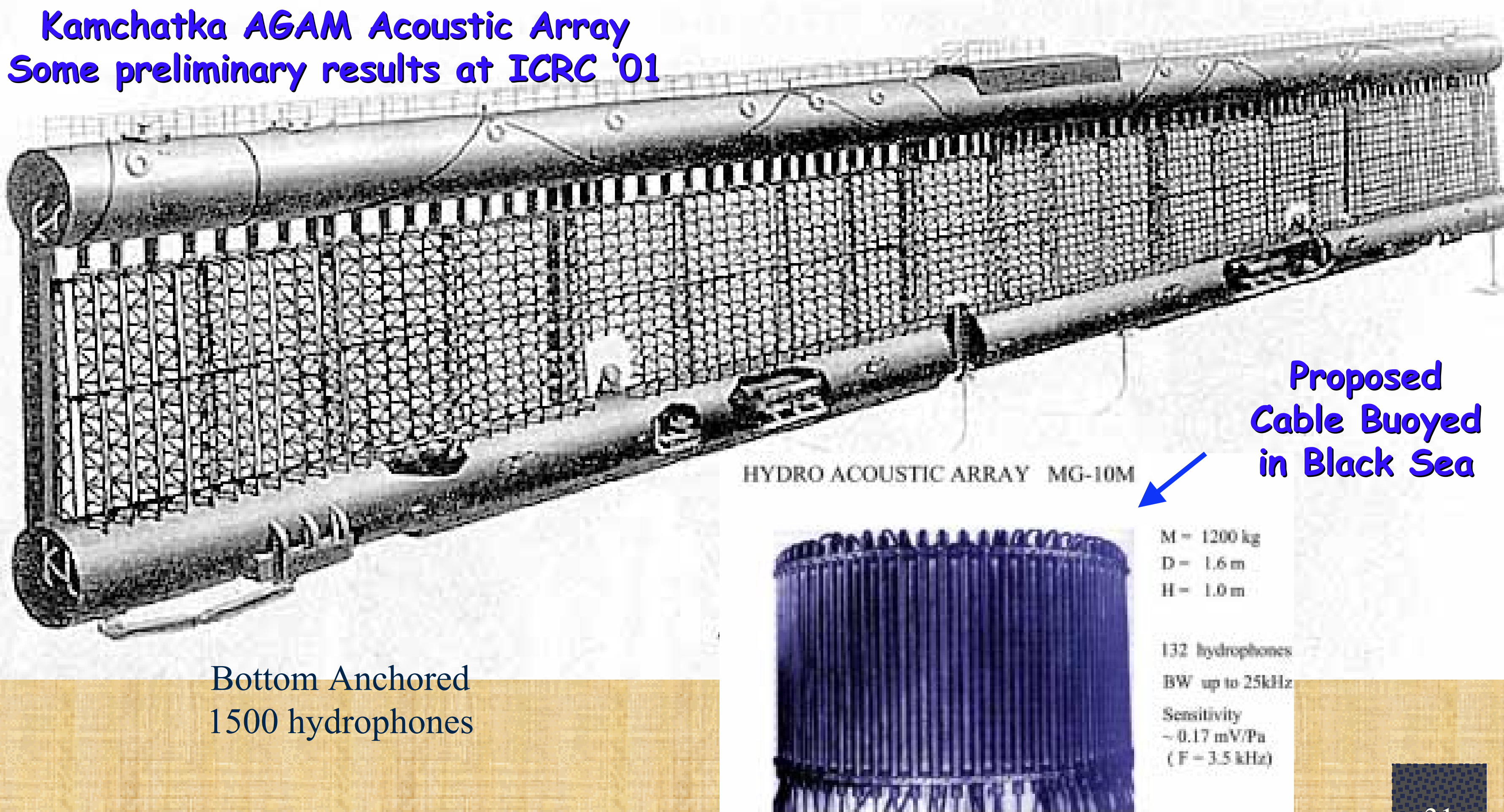


G. Gratta

Russian Acoustic Tests in Pacific and Black Sea

Kamchatka AGAM Acoustic Array
Some preliminary results at ICRC '01

Proposed Cable Buoyed in Black Sea



Bottom Anchored
1500 hydrophones

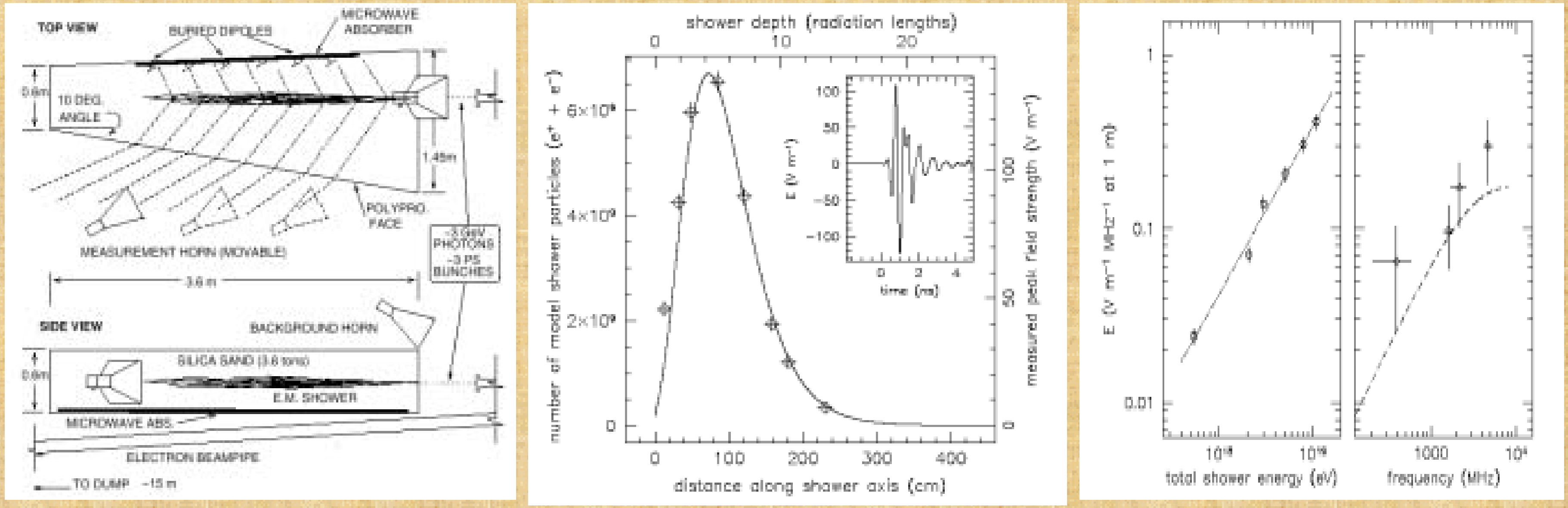
Summary of Acoustic Neutrino Detection

- Being revived after 20 years of little action: but now prospects for $>10^{20}$ eV neutrinos
- Advantages:
  - Potentially >> km^3 effective volumes
  - Well developed sonar technology
  - If salt practical, could use shear waves too → range
- Disadvantages:
  - Deep ocean impulsive backgrounds not yet well known
  - Small Signals, Threshold >> PeV
- Prospects:
  - Modest activity underway
  - Few years from dedicated experiment

Cascade Radio Emission:

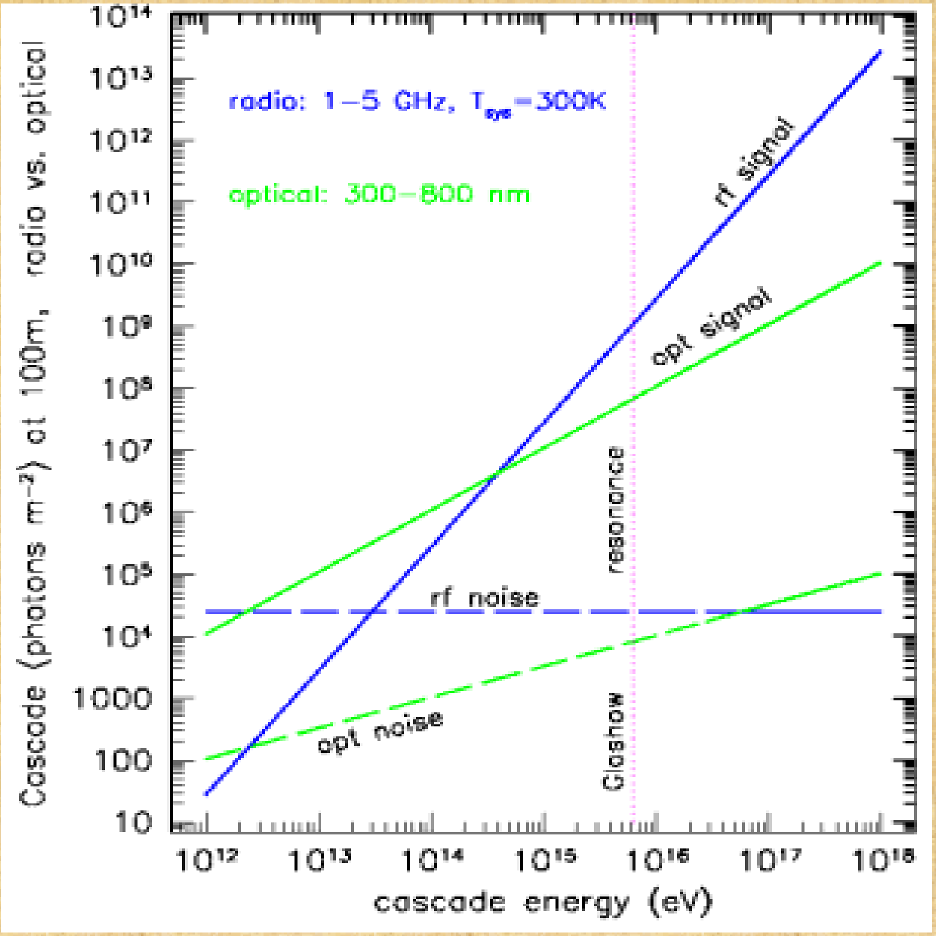
G. Askaryan 1962, pioneered by J. Jelley 1965, Renewed Activity Last Few Years

- Electromagnetic showers mostly γ's, e^+e^- : should be electrically neutral overall, thus *no net radio emission.*
- Scattering processes & positron annihilation lead to a 15-30% e^- excess.
- Radiates *coherent Cherenkov* radiation => Power ~ Energy^2
- Effect finally confirmed in 2000 at SLAC -- *strong effect !*



From Saltzberg, Gorham, Walz et al 2001, PRL

Detecting the TeV to EeV Cascades: Radio *vs.* Optical



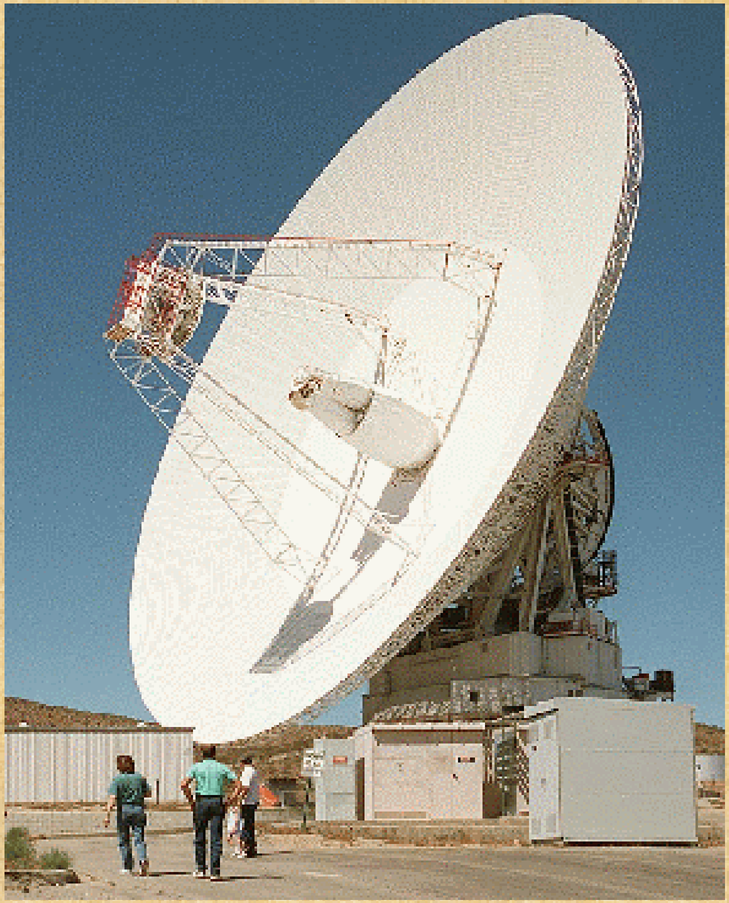
- Radio Cherenkov:
  - •broad spectrum, few MHz to ~10 GHz.
  - •intensity: Power ~ (Energy)^2, thermal noise constant.
  - •SNR >1 at >PeV energies for ~100 m range.
  - •needs radio-clear medium - cold ice or dry rock

- ***For >>PeV cascade detection, radio favored over optical.***

P. Gorham

Goldstone Lunar Ultra-high energy neutrino Experiment (GLUE)

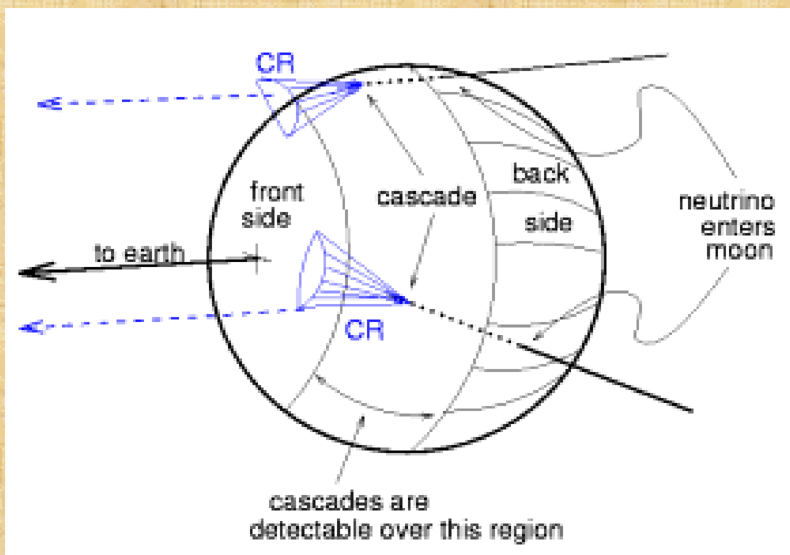
[Similar activity starting in Russia]

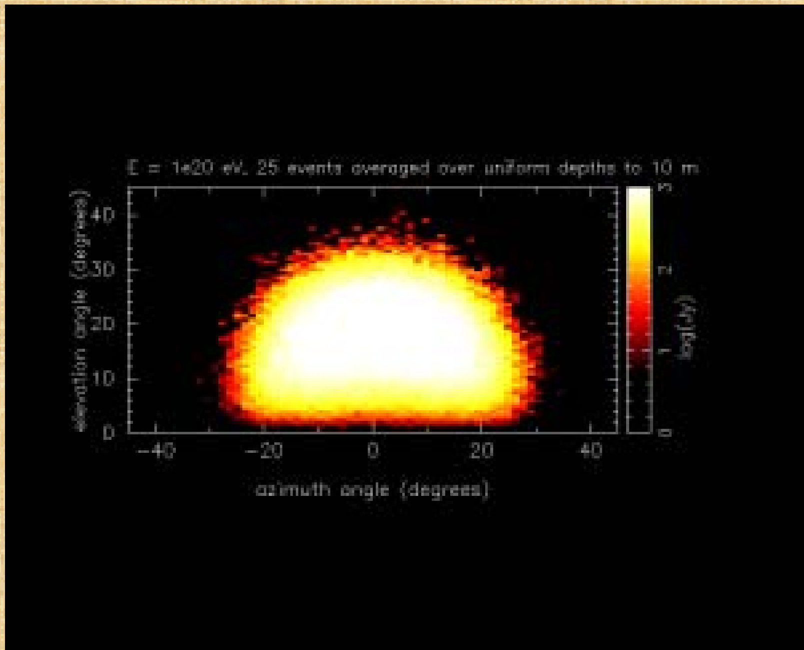


- Utilize NASA Deep Space telecom 70m antenna DSS14 for lunar RF pulse search--fill gaps in SC sched.
- First observations late 1998:
  - approach based on Hankins et al. 1996 results from Parkes 64 m telescope (10hrs live)
  - idea due to I. Zheleznykh, Neutrino `88
  - utilize active RFI veto
- Preliminary data taken 1999 through present, with continuing improvements in configuration and sensitivity.
- First results and limits available.

ν

Lunar Regolith Interactions & RF Cherenkov radiation



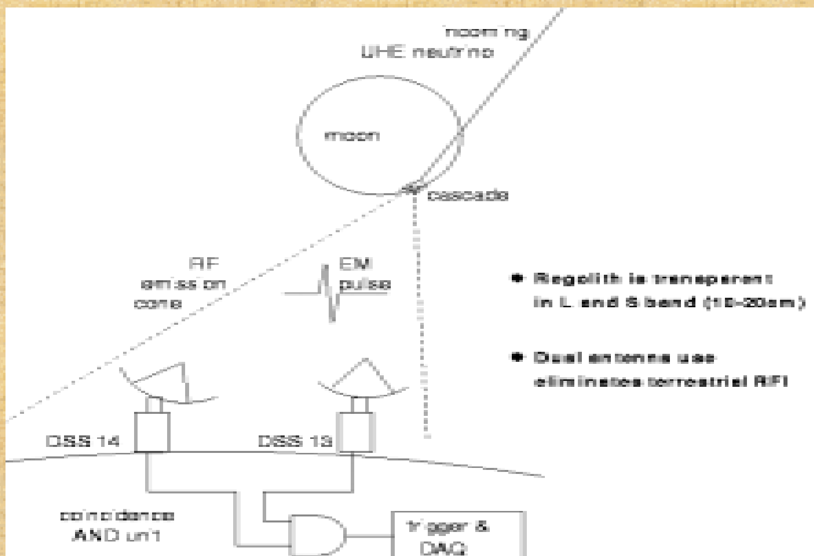


- At ~100 EeV energies, neutrino MFP in lunar material is ~60km.
- R_{moon} ~ 1760 km, so most detectable interactions are grazing rays, but detection not limited to just limb.
- Refraction of Cherenkov cone at regolith surface “fills in” the pattern, so acceptance solid angle is ~50 times larger than apparent solid angle of moon.

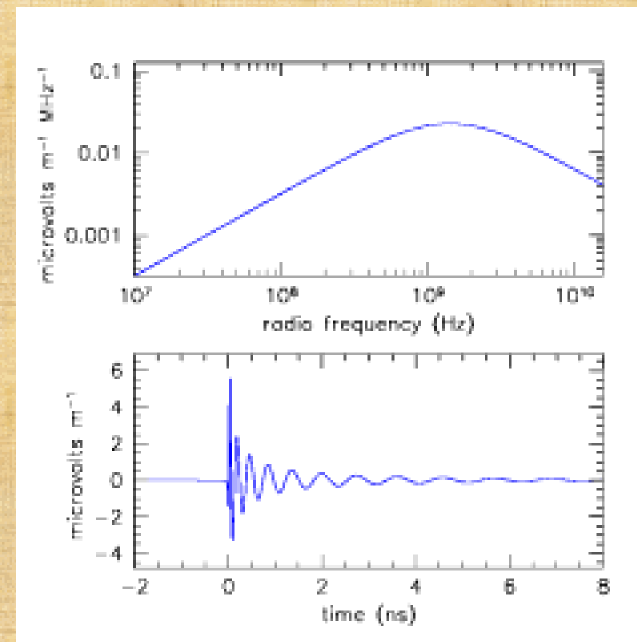
Goldstone DSN

Radio Detection Approach

P. Gorham



RF pulse spectrum & shape



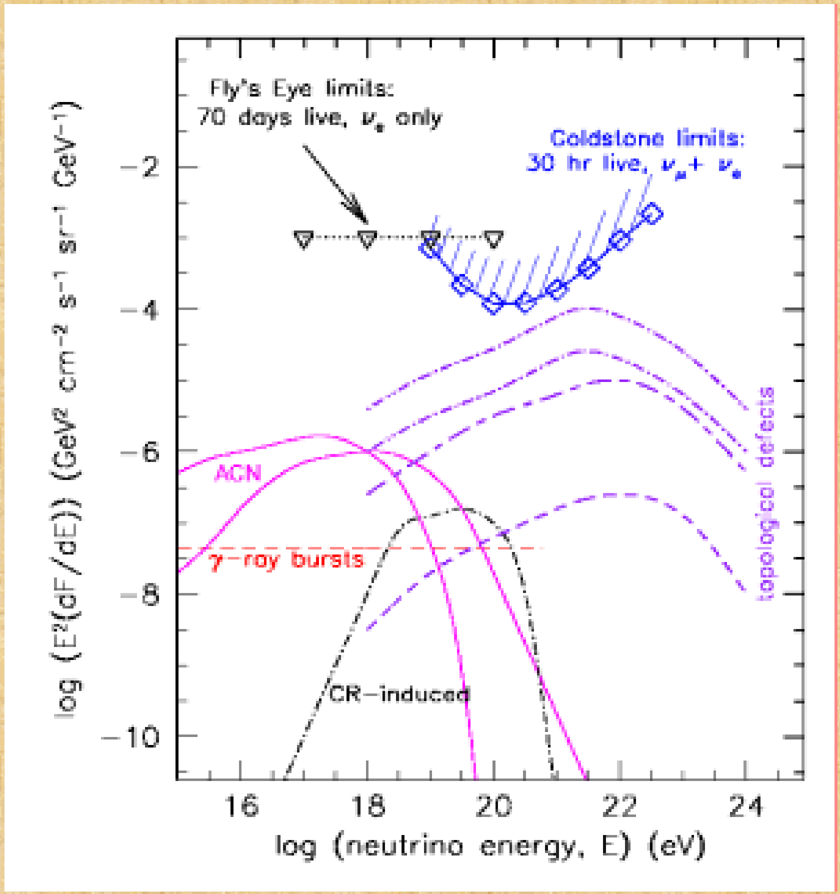
- Effective target volume: antenna beam (~0.3 deg) times ~10 m layer

  => ~100,000 cubic km !

- Limited primarily by livetime - small portion of antenna time devoted to any single project.

Goldstone

diffuse EHE neutrino flux limits

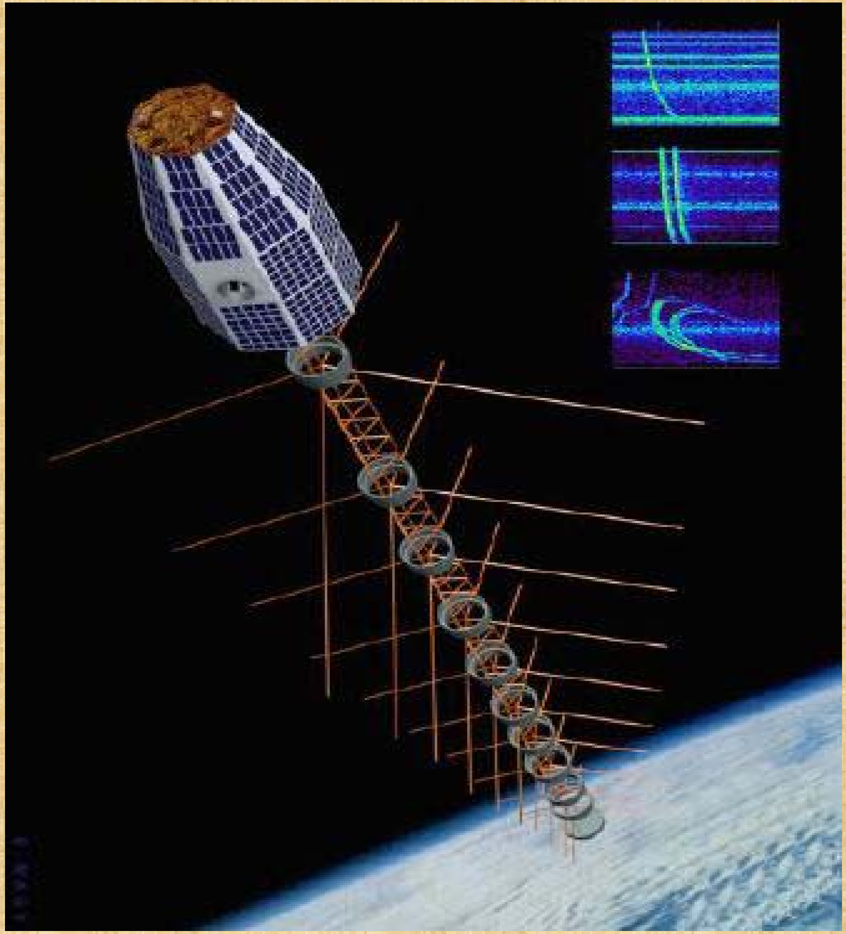


- ~30 hrs livetime
  - No events above net 5 sigma
- New Monte Carlo estimates:
  - cross-sections 'down' by 30-40%
  - Full refraction raytrace, including surface roughness, regolith absorption
  - Y-distribution, LPM included
- Limb observations:
  - lower threshold, but much less effective volume (factor of ~1/10)
  - 'Weaker' limit but with more confidence
- Fly's Eye limit: needs update:
  - Corrected (PG) by using published CR aperture, new neutrino cross sections.

P. Gorham

FORTE:

An Existing Space-based EHE Neutrino & Cosmic Ray Radio Detector?



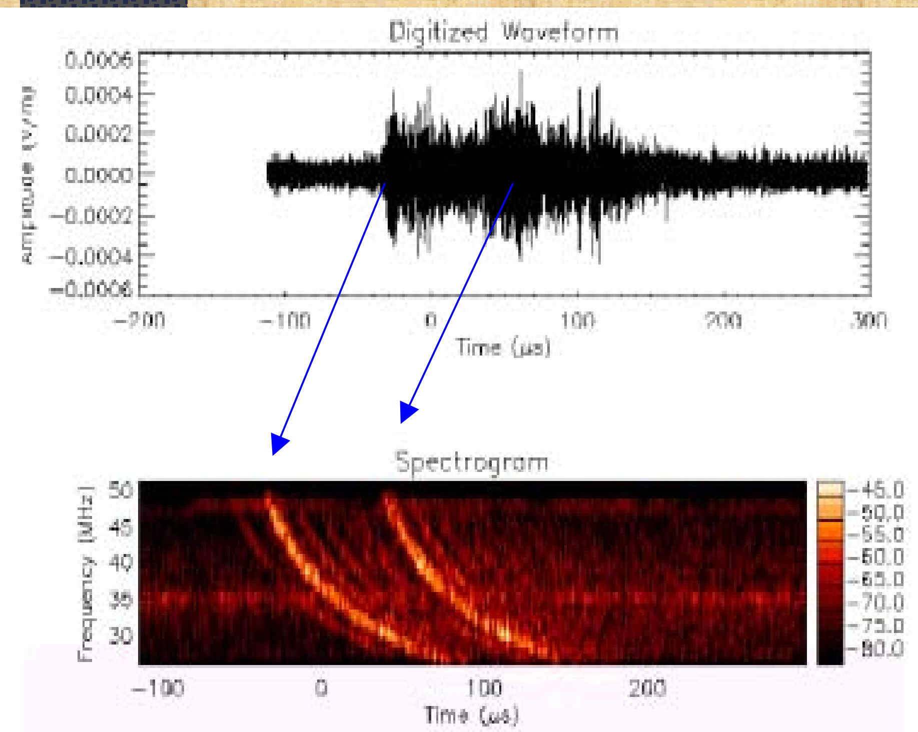
Fast On-orbit Radio Transient Expt.

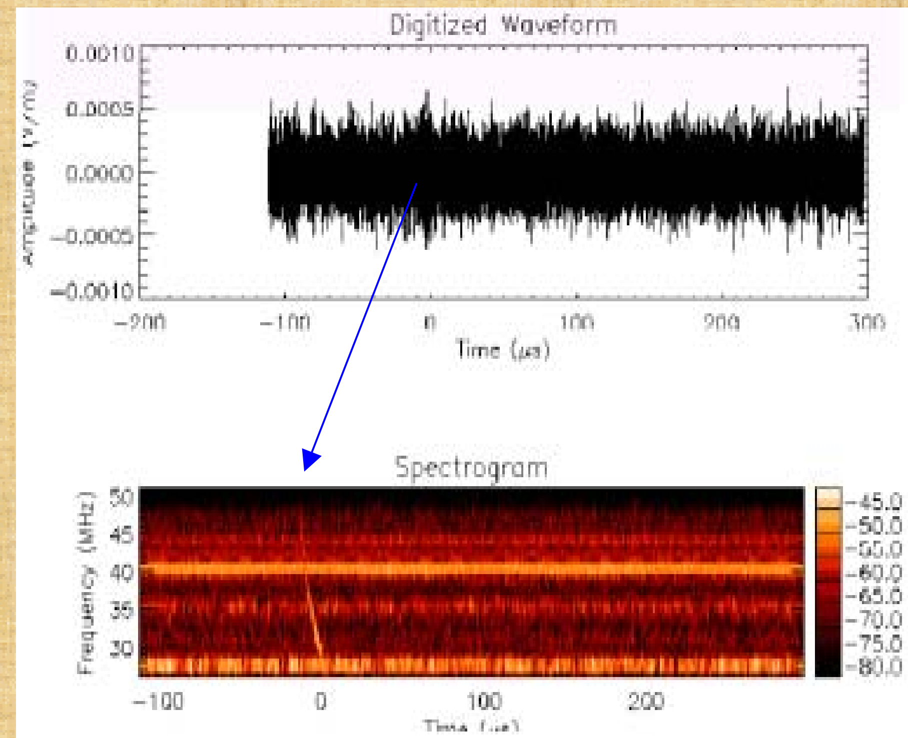
- Pegasus launch in 1997
  - 800 km orbit, 3 year planned life
  - Testbed for non-proliferation & verification sensing
  - Dept. of Energy funded, LANL & Sandia construction & operation
  - Scientific program in lightning & related atmospheric discharges
- 30-300MHz range, dual 20 MHz bands, 16 1MHz trigger channels
  - ~2M triggers recorded to date
- FORTE can trigger on radio emission from Giant air showers E~100 EeV
- Preliminary estimates: could be ~50-100 100 EeV cosmic ray events in sample
  - **Analysis (UH, JPL, LANL) in progress; limits soon.**

FORTE

Data Examples

V

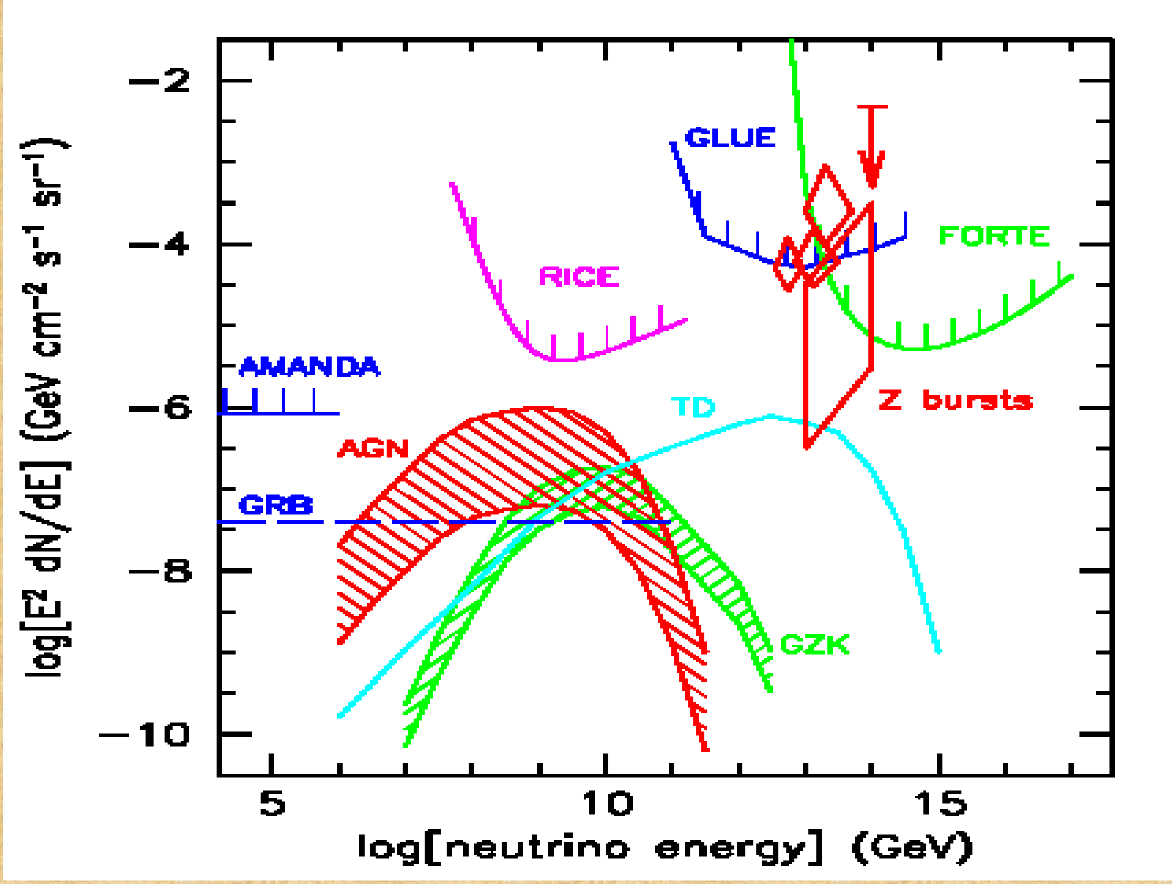




- **Typical lightning trigger**
  - dispersion (curvature) due to ionosphere
  - multiple strikes
- Correlated to ground-based networks

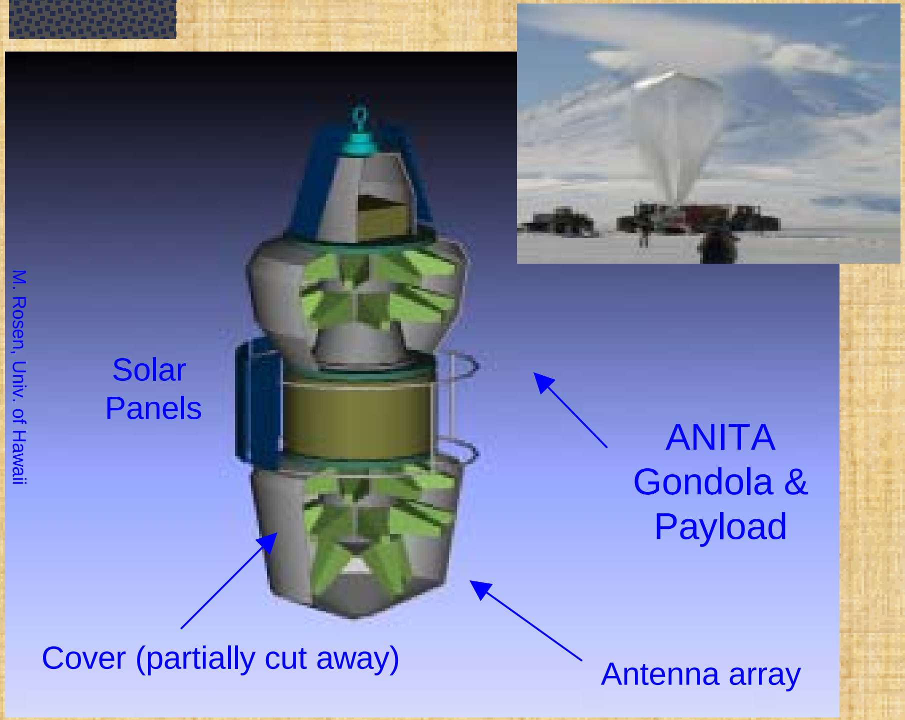
- **Isolated trigger**
  - Band-limited, very short duration
  - No pre- or post-trigger pulses close
  - No related pulses within several sec

Limits from FORTE and GLUE



see astro/ph0309656 and astro/ph0310232

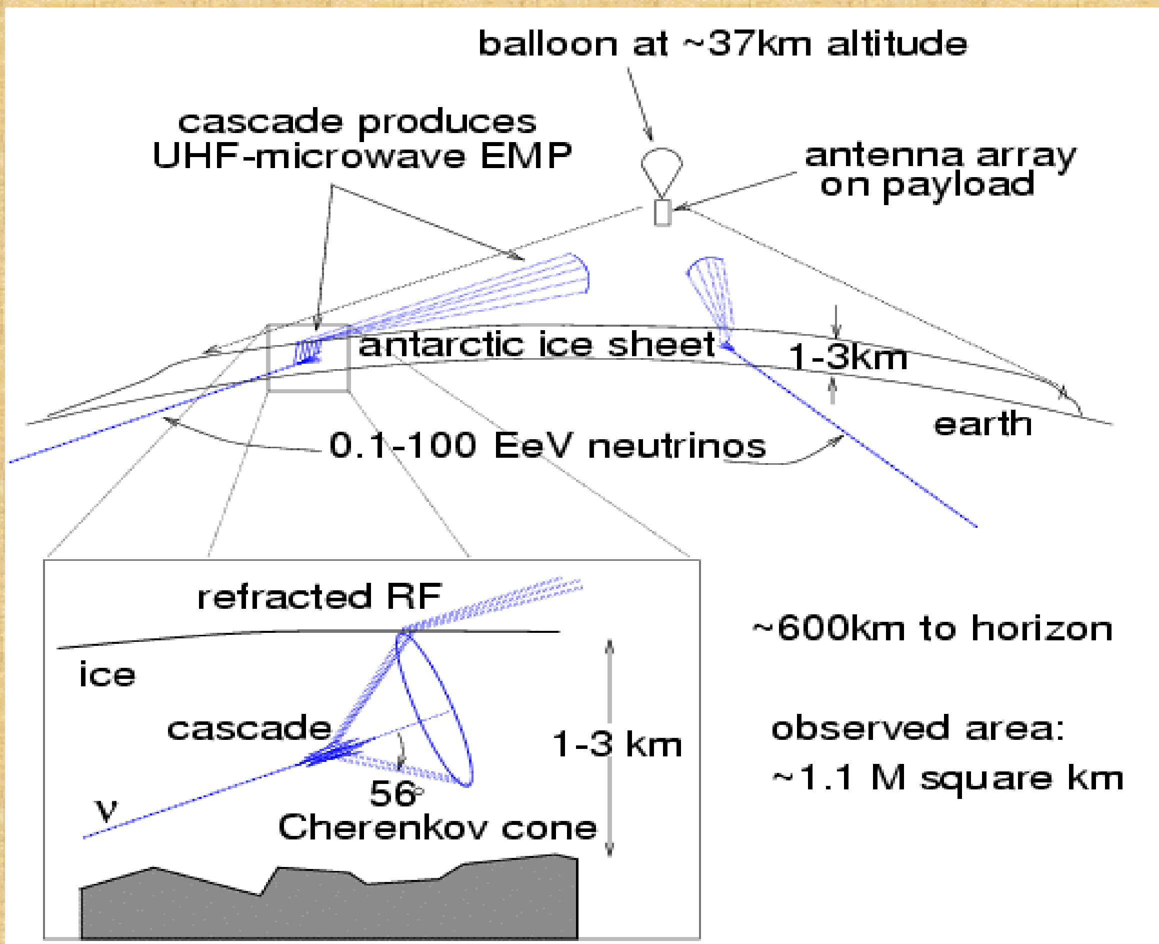
Antarctic Impulsive Transient Antenna (ANITA)

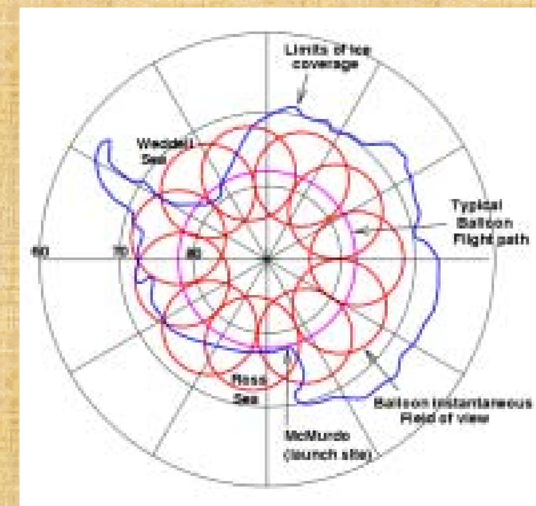


- ANITA Goal: Pathfinding mission for ultra-high energy cosmic neutrinos.
- Science team: P. Gorham (PI), S. Barwick (UCI), J. Beatty, S. Coutu (Penn State), P. Evenson, J. Clem, D. Seckel (U.Del./Bartol), F. Halzen (Wisconsin), D. Kieda (Utah), J. Learned (UH), D. Saltzberg (UCLA), K. Liewer, S. Lowe, C. Naudet (JPL), A. Jacobson (LANL)

ANITA

Radio from EeV ν's in Polar Ice





- NASA approved 2002
- Successful test flight 1/04
- Data in 2007

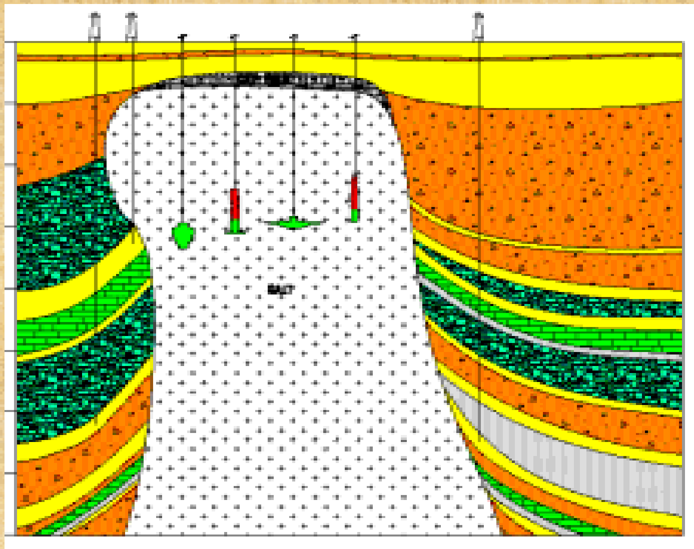
Radio Detection in Natural Salt Domes

SALSA

V

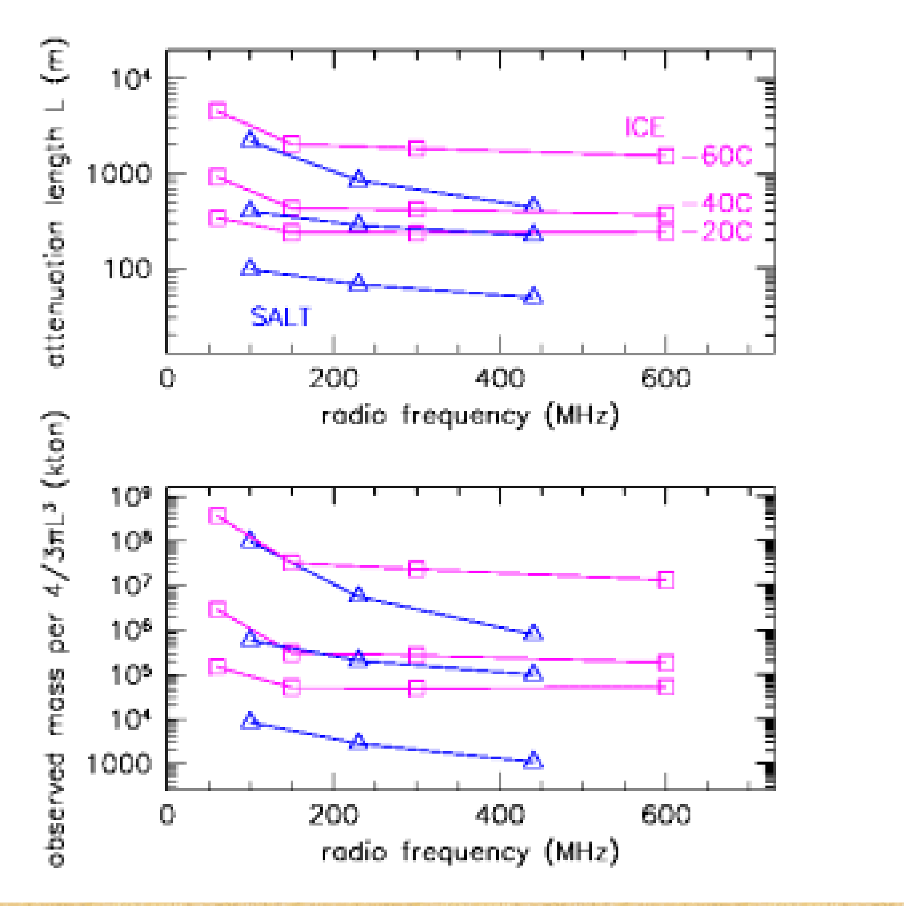
• Natural salt can be extremely low RF loss: ~ as clear as very cold ice, but nearly 2.5 times as dense.

• Typical salt dome halite is comparable to ice at -40C for RF clarity.



5-10km

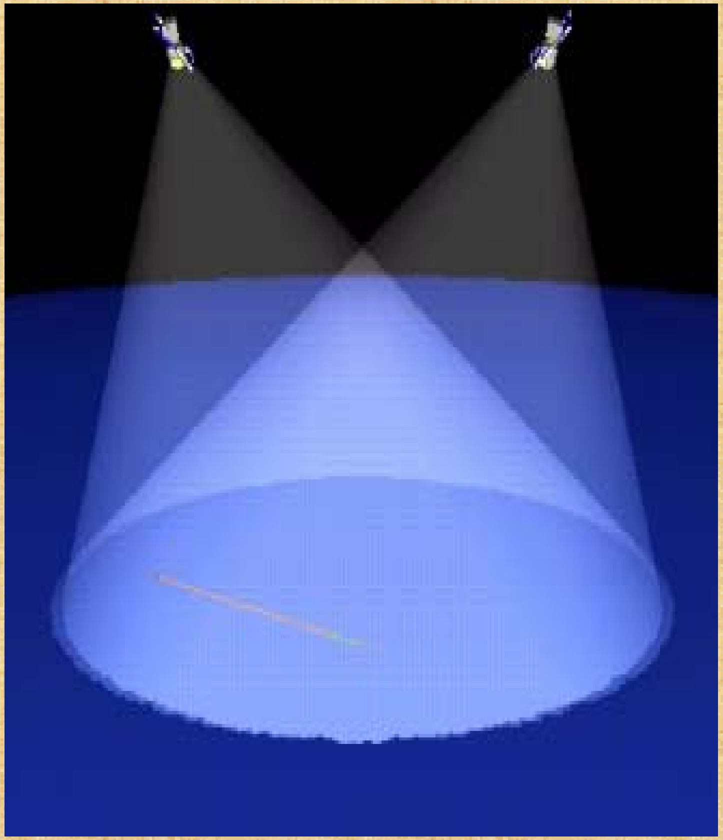
3-5 km



SALT curves are for (top): purest natural salt; (middle): typical good salt dome; (bottom) best salt bed halite. New measurements 2001, SLAC 2002.

All Experiments Built to Explore GZK Anomaly are also ν Telescopes

- Limits from Fly's Eye, AGASA, Hi-Res …
- Better limits will come from **ground** (Auger) and **space** (EUSO/OWL/….)
  - **Area large, solid angle is small; but may measure GZK Neutrinos**

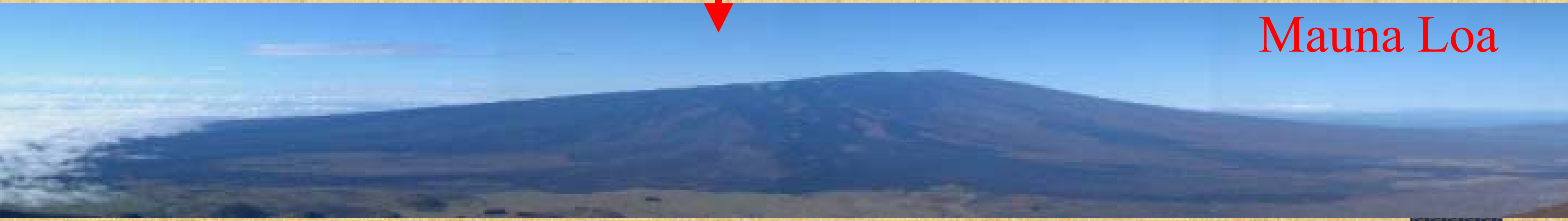


J. Krizmanic

- Plus seeing neutrinos exiting ground: NuTeL

NuTel: Tau Watch in Hawaii
Neutrinos Converted in Mountain

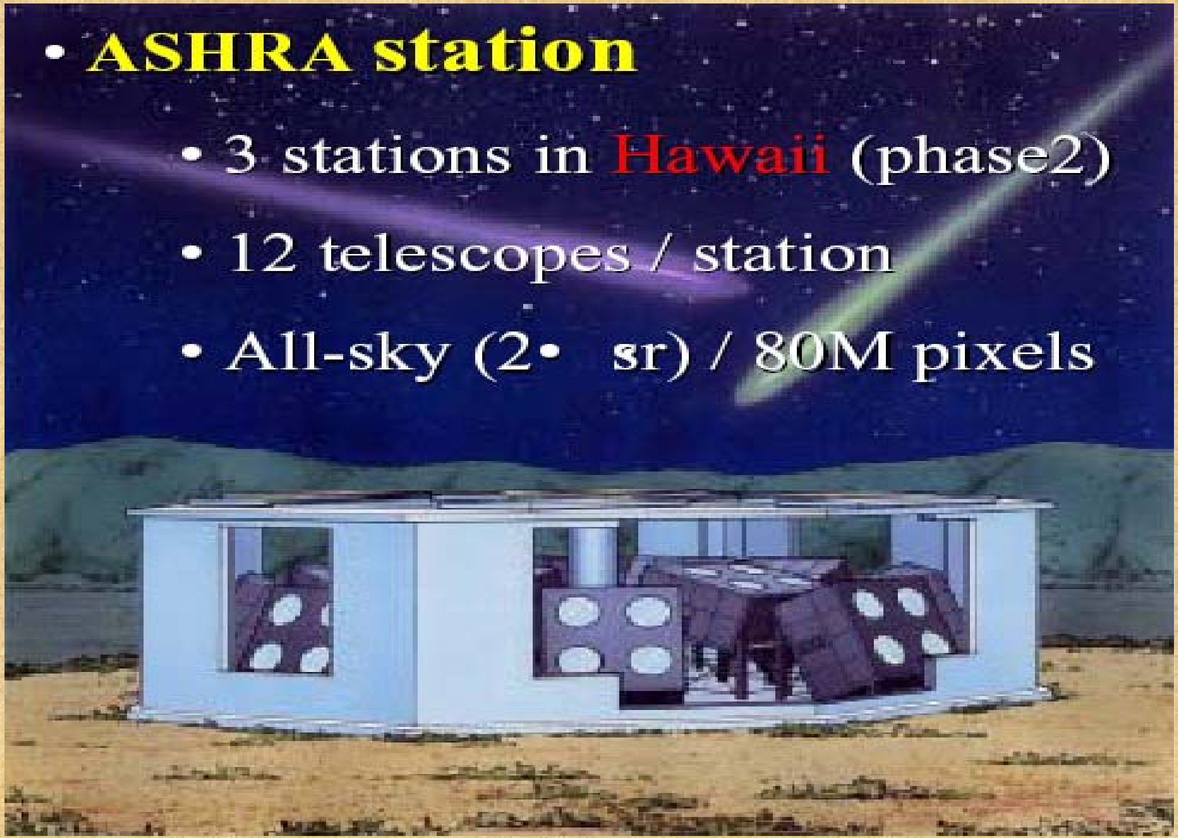
- Astronomer's dream site
  - Excellent weather
  - Little artificial light
- 3km Mt. Hualalai provides good view of Mauna Loa.
- Mauna Loa provide long base line, ~ 90 km wide and 4 km high.



ASHRA

V

New Project Combining Air Cherenkov and Fluorescence Detection

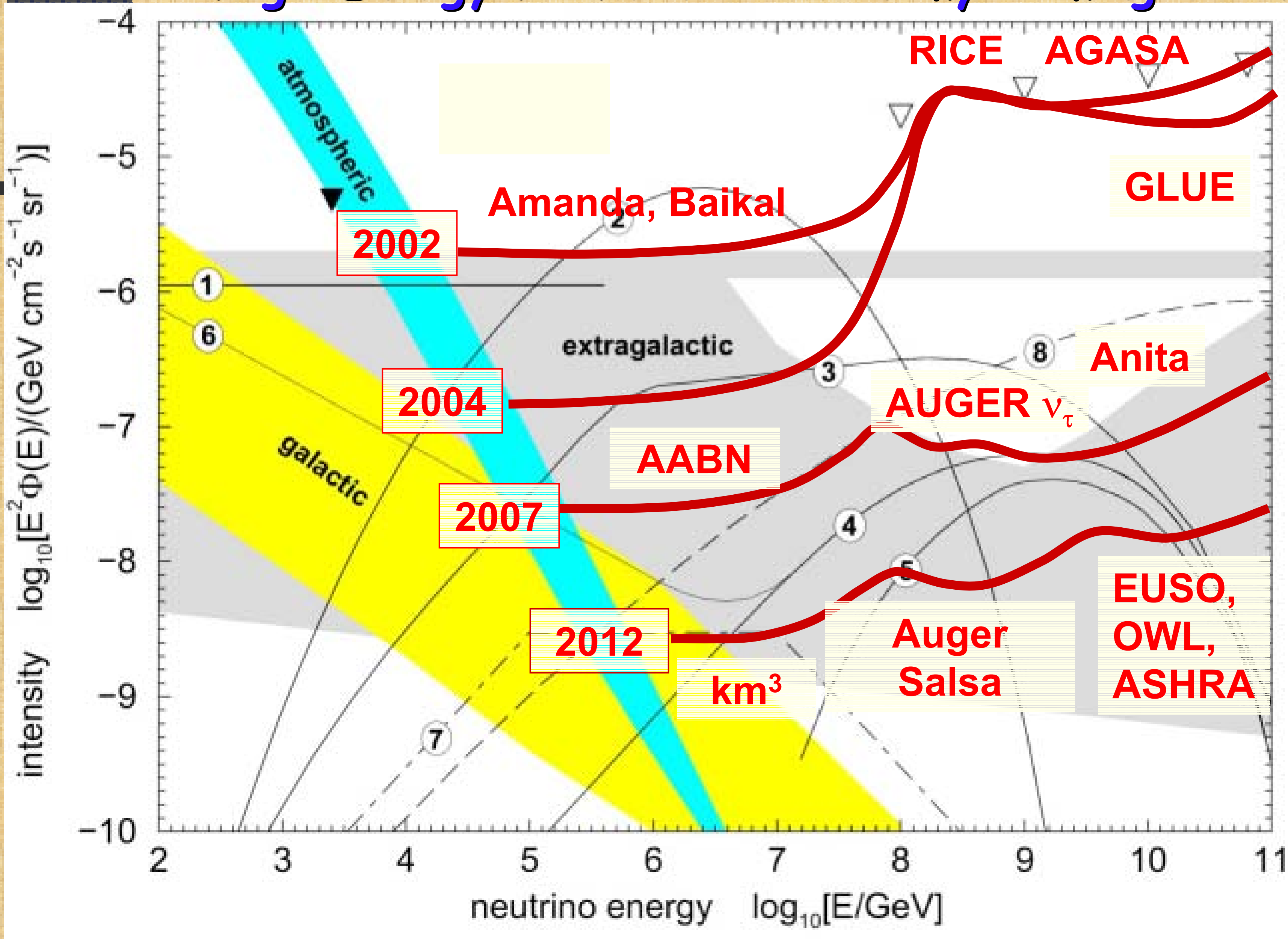


$0.04/pixel

Test Telescope on Haleakala in '03

M. Sasaki U. Tokyo ICRR

High Energy Neutrino Astronomy Coming Soon!



projection by Christian Spiering, 10/02

Lots New in ν Astronomy

- **It is a very exciting time in the neutrino business!**
- Much activity: ~**dozen projects** in motion around world.
- Next few years will see:
  - $\geq$1 optical Cherenkov **array in Mediterranean,**
  - Huge **ICECUBE** km^3 array in 2 km deep ice South Pole,
  - Significant limits and possible discovery of **E.H.E. ν's** in
    - EAS detectors (counter, air fluor & radio),
    - Explorations with acoustics and new radio tech.
- ANITA and ASHRA are exciting new players!