Some Lessons Learned from Deep Oceanographic Neutrino Telescopes

John G. Learned
University of Hawaii

This draws upon my 2019 Neutrino Telescopes talk about the history and future of neutrino astronomy. There I quoted many slides from Amy Connelly at ARENA2018... excellent summary talk. Christian Spiering helped greatly with the tables of past, current and future projects. The comments and lessons are from my own experience with attempts at neutrino astronomy from the 1970’s onwards and particularly as head of DUMAND through the 80’s and into the 90’s.
Beginnings of HE Nu Astronomy

• The journey to high energy neutrino astronomy starts with fantastic dreams in Russia and US in 1950’s with pioneers such as Moisei Markov, George Zatsepin, in Russia and Ken Greisen, and Fred Reines in the USA, and who first articulated the dream of detecting cosmic neutrinos, hopefully permitting us to view the universe in a very different light than photons. (Ref. Markov1960)

• 1969 Berezinsky and Zatsepin propose the generation of neutrinos due to the GZK cutoff in cosmic protons $\sim 10^{20}$ eV. (Still not seen!)

• DUMAND Begins at talks in 1973, International Cosmic Ray Conference (ICRC) F. Reines, J. Learned, H. Davis, P. Kotzer, M. Shapiro (all USA), G. Zatsepin (USSR) and S. Miyake (Japan) discuss a deep-water detector.
The Real Birth of the present quest 1976
DUMAND Summer Workshop

- Basically we had no idea what we were doing...
- Had ideas about starting neutrino astronomy from deep below the earth surface, with water or sold targets.
- No prior guidance as to best chances with
  - High energy (>> GeV) neutrinos or
  - Low energy (1-100 MeV) neutrinos
- Almost no prior estimates of flux at high energies... astrophysicist did not think neutrinos
- No prior guidance about best detection mechanisms
We knew what it would take
40 years Ago!

1978: DUMAND
First design of a cubic kilometer
detector to be in deep ocean Hawaii

- While exploring other techniques
  we knew that optical detectors would
do the job
- Large PMTs in glass housings practical
- New techniques (radio, acoustic) were
  known to be for > TeV energies
- No reasonable predicted fluxes at > PeV
- Lower energy regime aimed at Atm Nus,
solar and SN
- Made first designs for large underground
detectors for the lower energy regime,
in particular IMB, Kamiokande, and HPW
1980’s Saw First Large Nu Detectors

- Race to find proton decay, PDK… still none!
- IMB & Kam found “Muon Neutrino Anomaly”, controversial through decade
- Kamiokande observed solar neutrinos!
- Kam, IMB and Baksan observed SN1987A
- Despite scans of sky maps of atmospheric neutrino directions, no hint of cosmic nus
Future of High Energy Neutrino Astronomy

John G. Learned

Department of Physics and Astronomy, University of Hawaii, Manoa
2505 Correa Road, Honolulu, HI 96822 USA

Abstract

The present status of experiments and prospects for future high energy neutrino astrophysics endeavors are summarized. Present and near-future underground experiments (7 mine based detectors, in the 100 - 1000 m$^2$ muon detection area range) may not be large enough to detect point sources of neutrinos. However, it seems that there are perhaps 6 third generation detectors (in the >10,000 m$^2$ class) in various stages of proposal, test or construction. Some of these will come to operation by the mid-nineties. The DUMAND II detector, now in construction for deployment in Hawaii for operation beginning in 1993, is described in some detail. Several novel detection techniques being explored elsewhere, particularly in the Antarctic, are briefly mentioned. Finally, it is pointed out that discussions are beginning for a much larger detector (or detectors) in the $10^6$ m$^2$ class to be built around the turn of the century, conditionally upon the success of the next generation of instruments now under active testing and construction.

HDC-8-90
submitted to
Proceedings of the Venice Workshop on "Neutrino Telescopes",
13-15 February 1990
DUMAND Nostalgia  Circa 1990

Done 1989

Only cable J-box and Monitoring Deployed

Intended for 1993
Table I
Summary of large underground instruments with high energy neutrino detection capability, 1960's through mid 1990's.

<table>
<thead>
<tr>
<th>Detector, Location</th>
<th>Status</th>
<th>( \mu ) Area Dir (m²)</th>
<th>Technique</th>
<th>Primary Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>KGF, South India</td>
<td>X</td>
<td>110 N</td>
<td>LS + FT</td>
<td>obs ( \nu )'s</td>
</tr>
<tr>
<td>CWI, South Africa</td>
<td>X</td>
<td>10 N</td>
<td>PS + FT + Fe</td>
<td>obs ( \nu )'s</td>
</tr>
<tr>
<td>Silver King, Utah</td>
<td>X</td>
<td>30 Y</td>
<td>WC + Ctrs + Fe</td>
<td>obs ( \nu )'s</td>
</tr>
<tr>
<td>KGF, South India</td>
<td>R</td>
<td>20 N</td>
<td>St Tubes</td>
<td>PDK</td>
</tr>
<tr>
<td>Baksan, Caucasus</td>
<td>R</td>
<td>250 Y</td>
<td>LS tanks</td>
<td>( \nu )'s</td>
</tr>
<tr>
<td>IMB, Ohio</td>
<td>R</td>
<td>400 Y</td>
<td>WC</td>
<td>PDK</td>
</tr>
<tr>
<td>HPW, Utah</td>
<td>X</td>
<td>100 Y</td>
<td>WC</td>
<td>PDK</td>
</tr>
<tr>
<td>Kamioka, Japan</td>
<td>R</td>
<td>120 Y</td>
<td>WC</td>
<td>PDK</td>
</tr>
<tr>
<td>NUSEX, Mt Blanc</td>
<td>R</td>
<td>10 N</td>
<td>ST + Fe</td>
<td>PDK</td>
</tr>
<tr>
<td>Frejus</td>
<td>X</td>
<td>90 N</td>
<td>ST + Fe</td>
<td>PDK</td>
</tr>
<tr>
<td>Soudan I</td>
<td>R</td>
<td>10 N</td>
<td>ST + Concrete</td>
<td>PDK</td>
</tr>
<tr>
<td>Soudan II</td>
<td>C/P</td>
<td>100 N</td>
<td>DT + Concrete</td>
<td>PDK</td>
</tr>
<tr>
<td>MACRO</td>
<td>C/P</td>
<td>1100 Y</td>
<td>LS + ST +</td>
<td>Monopoles</td>
</tr>
<tr>
<td>LVD</td>
<td>C</td>
<td>800 Y</td>
<td>LS tanks + ST</td>
<td>SN ( \nu )'s</td>
</tr>
<tr>
<td>SNO</td>
<td>C</td>
<td>300 Y</td>
<td>( D_2O )</td>
<td>Solar ( \nu )'s</td>
</tr>
<tr>
<td>SuperKamiokande</td>
<td>P&lt;96</td>
<td>740 Y</td>
<td>WC</td>
<td>PDK</td>
</tr>
<tr>
<td>Borex</td>
<td>P</td>
<td>&lt;100 Y</td>
<td>LS</td>
<td>Solar ( \nu )'s</td>
</tr>
</tbody>
</table>

Key for Table:
- P = proposal
- T = testing and development
- C = construction
- R = operating
- X = shut down

\( WC \) = water Cherenkov
\( ST \) = streamer tubes
\( LS \) = liquid scintillator
\( PS \) = plastic scintillator
\( FT \) = flash tubes
### 1990 Summary of then New Initiatives

Table II
Summary of new initiatives in high energy neutrino astronomy.

<table>
<thead>
<tr>
<th>Detector</th>
<th>Location</th>
<th>Status</th>
<th>$\mu$ Area (m$^2$)</th>
<th>Depth (mwe)</th>
<th>Techn</th>
<th>Threshold</th>
</tr>
</thead>
<tbody>
<tr>
<td>DUMAND II</td>
<td>Hawaii</td>
<td>X'93</td>
<td>20,000</td>
<td>4,800</td>
<td>WC</td>
<td>20 GeV</td>
</tr>
<tr>
<td>Baykal DUMAND</td>
<td>Siberia</td>
<td>X'95</td>
<td>2,000</td>
<td>1,200</td>
<td>WC</td>
<td>10 GeV</td>
</tr>
<tr>
<td>SINGAO</td>
<td>S. Italy</td>
<td>X</td>
<td>15,000</td>
<td>10-0</td>
<td>RPC</td>
<td>2 GeV</td>
</tr>
<tr>
<td>GRANDE</td>
<td>Arkansas</td>
<td>X</td>
<td>30,800</td>
<td>0-50</td>
<td>WC</td>
<td>6 GeV</td>
</tr>
<tr>
<td>GRANDE type</td>
<td>Gran Sass</td>
<td>X</td>
<td>100,000?</td>
<td>0-65?</td>
<td>WC</td>
<td>8 GeV?</td>
</tr>
<tr>
<td>?? Medit. DUM</td>
<td>SW Grec?</td>
<td>P/D/T</td>
<td>?</td>
<td>4,000</td>
<td>WC</td>
<td>?</td>
</tr>
<tr>
<td>?? Sov. DUM, East</td>
<td>Pacific?</td>
<td>D/T</td>
<td>?</td>
<td>?</td>
<td>WC</td>
<td>?</td>
</tr>
<tr>
<td>?? GRANDE type</td>
<td>USSR</td>
<td>X</td>
<td>?</td>
<td>0-?</td>
<td>WC</td>
<td>?</td>
</tr>
<tr>
<td>?? LENA</td>
<td>Japan?</td>
<td>X</td>
<td>?</td>
<td>0-?</td>
<td>WC</td>
<td>?</td>
</tr>
<tr>
<td>?? GRANDE type</td>
<td>Austral</td>
<td>X</td>
<td>?</td>
<td>0-?</td>
<td>WC</td>
<td>?</td>
</tr>
<tr>
<td>SPICE</td>
<td>S. Pole</td>
<td>X</td>
<td>?</td>
<td>&gt;1,000</td>
<td>WC in ice?</td>
<td></td>
</tr>
<tr>
<td>RAMAND</td>
<td>Antarct</td>
<td>X</td>
<td>$10^6$</td>
<td>0-1,000</td>
<td>ice $\mu$wv</td>
<td>&gt;100 TeV</td>
</tr>
<tr>
<td>?? World Detector</td>
<td>?</td>
<td>X</td>
<td>$10^6$</td>
<td>&gt;4,000</td>
<td>WC</td>
<td>&gt;100 GeV</td>
</tr>
</tbody>
</table>

Key for Table:
- D = discussion
- P = proposal (possible operational date)
- T = testing and development
- C = construction (operational date)
- WC = water Cherenkov detector
- RPC = resistive plate chamber
- $\mu$wv = microwave detection
## 2019 Recent, Operating and Imminent Large Natural Neutrino Projects; 16, 6 Operating

<table>
<thead>
<tr>
<th>Project</th>
<th>Location</th>
<th>Status</th>
<th>Area / Vol</th>
<th>Solid Angle</th>
<th>Energy</th>
<th>Technology</th>
<th>Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>BaikalNT200</td>
<td>Siberia</td>
<td>X</td>
<td>2000 m²</td>
<td>$2\pi$</td>
<td>10 GeV</td>
<td>WC</td>
<td>v astr</td>
</tr>
<tr>
<td>SAGE</td>
<td>Baksan</td>
<td>O</td>
<td>50 T</td>
<td>$4\pi$</td>
<td>0.1 MeV</td>
<td>Gal.</td>
<td>Solar</td>
</tr>
<tr>
<td>AMANDA</td>
<td>So. Pole</td>
<td>X</td>
<td>3x10⁴ m²</td>
<td>$4\pi$</td>
<td>50 GeV</td>
<td>IC</td>
<td>v astr</td>
</tr>
<tr>
<td>Auger</td>
<td>Argent.</td>
<td>O</td>
<td>3x10⁴ km²</td>
<td>$2\pi$</td>
<td>EeV</td>
<td>AC</td>
<td>EAS</td>
</tr>
<tr>
<td>IceCube</td>
<td>So. Pole</td>
<td>O</td>
<td>1 km²</td>
<td>$4\pi$</td>
<td>100 GeV</td>
<td>IC</td>
<td>v astr</td>
</tr>
<tr>
<td>Borexino</td>
<td>Gr. Sasso</td>
<td>O&gt;X</td>
<td>100 T</td>
<td>$4\pi$</td>
<td>1 MeV</td>
<td>LS</td>
<td>Solar</td>
</tr>
<tr>
<td>NESTOR</td>
<td>Greece</td>
<td>X</td>
<td>10⁴ m²</td>
<td>$2\pi$</td>
<td>GeV</td>
<td>WC</td>
<td>v astr</td>
</tr>
<tr>
<td>NEMO</td>
<td>Sicily</td>
<td>X</td>
<td>10⁴ m²</td>
<td>$2\pi$</td>
<td>GeV</td>
<td>WC</td>
<td>v astr</td>
</tr>
<tr>
<td>Antares</td>
<td>France</td>
<td>O</td>
<td>3x10⁴ m²</td>
<td>$2\pi$</td>
<td>20 GeV</td>
<td>WC</td>
<td>v astr</td>
</tr>
<tr>
<td>SuperK</td>
<td>Japan</td>
<td>O</td>
<td>22 kT</td>
<td>$4\pi$</td>
<td>4 MeV</td>
<td>WC</td>
<td>PDK</td>
</tr>
<tr>
<td>SNO</td>
<td>Canada</td>
<td>X</td>
<td>1 kT</td>
<td>$4\pi$</td>
<td>2 MeV</td>
<td>HWC</td>
<td>sv astr</td>
</tr>
<tr>
<td>KamLAND</td>
<td>Japan</td>
<td>O</td>
<td>600 T</td>
<td>$4\pi$</td>
<td>1.8 MeV</td>
<td>LS</td>
<td>rv osc</td>
</tr>
<tr>
<td>Anita</td>
<td>Antarctic</td>
<td>X</td>
<td>10⁶ km²</td>
<td>$10^{-6}$</td>
<td>5 EeV</td>
<td>ICR</td>
<td>v astr</td>
</tr>
<tr>
<td>ARA</td>
<td>So. Pole</td>
<td>C</td>
<td>100 km²</td>
<td>$2\pi$</td>
<td>~ EeV</td>
<td>IR</td>
<td>v astr</td>
</tr>
<tr>
<td>Arianna</td>
<td>Antarctic</td>
<td>C</td>
<td>10 km²</td>
<td>$2\pi$</td>
<td>&gt;EeV</td>
<td>IR</td>
<td>v astr</td>
</tr>
<tr>
<td>SNO+</td>
<td>Canada</td>
<td>T</td>
<td>800 T</td>
<td>$4\pi$</td>
<td>2 MeV</td>
<td>LS</td>
<td>DBD</td>
</tr>
<tr>
<td>project</td>
<td>loc</td>
<td>st</td>
<td>area/vol</td>
<td>En. thr.</td>
<td>tech</td>
<td>goal</td>
<td></td>
</tr>
<tr>
<td>-----------------------</td>
<td>-------------</td>
<td>----</td>
<td>---------------</td>
<td>----------</td>
<td>------</td>
<td>------------</td>
<td></td>
</tr>
<tr>
<td>ASHRA</td>
<td>Hawaii</td>
<td>P?</td>
<td>20 km²</td>
<td>EeV?</td>
<td>AC</td>
<td>v astr</td>
<td></td>
</tr>
<tr>
<td>Pueo</td>
<td>So. Pole</td>
<td>P</td>
<td>10⁶ km²</td>
<td>3 EeV</td>
<td>IR</td>
<td>v astr</td>
<td></td>
</tr>
<tr>
<td>IceCube-Gen2</td>
<td>So. Pole</td>
<td>P</td>
<td>9 km²</td>
<td>10 TeV</td>
<td>IC</td>
<td>v astr</td>
<td></td>
</tr>
<tr>
<td>ARA+</td>
<td>So. Pole</td>
<td>P</td>
<td>120 km²</td>
<td>50 PeV</td>
<td>IR</td>
<td>v astr</td>
<td></td>
</tr>
<tr>
<td>Baikal-GVD</td>
<td>Siberia</td>
<td>C</td>
<td>0.4&gt;2 km²</td>
<td>100 GeV</td>
<td>WC</td>
<td>v astr</td>
<td></td>
</tr>
<tr>
<td>Baksan Scint. Det.</td>
<td>Caucasus</td>
<td>P</td>
<td>10 kT</td>
<td>100 MeV</td>
<td>LS</td>
<td>v astr</td>
<td></td>
</tr>
<tr>
<td>HyperKam.</td>
<td>Japan</td>
<td>T/C</td>
<td>260 kT</td>
<td>6 MeV</td>
<td>WC</td>
<td>v osc/pdk</td>
<td></td>
</tr>
<tr>
<td>Jinping</td>
<td>China</td>
<td>P</td>
<td>3000 T</td>
<td>1 MeV</td>
<td>LS</td>
<td>geo v</td>
<td></td>
</tr>
<tr>
<td>DUNE</td>
<td>Homestake</td>
<td>C</td>
<td>34 kT</td>
<td>100 MeV</td>
<td>LAr</td>
<td>v osc</td>
<td></td>
</tr>
<tr>
<td>Theia</td>
<td>Homestake</td>
<td>P</td>
<td>50 kT</td>
<td>2 MeV</td>
<td>LS</td>
<td>v astr</td>
<td></td>
</tr>
<tr>
<td>GRAND</td>
<td>China</td>
<td>P</td>
<td>2x10⁵km²</td>
<td>100 PeV</td>
<td>RC</td>
<td>v astr</td>
<td></td>
</tr>
<tr>
<td>Pingu</td>
<td>So. Pole</td>
<td>P</td>
<td>6 MT</td>
<td>8 GeV</td>
<td>IC</td>
<td>v osc</td>
<td></td>
</tr>
<tr>
<td>KM3NET/ORCA</td>
<td>Mediter.</td>
<td>C</td>
<td>8 MT</td>
<td>10 GeV</td>
<td>WC</td>
<td>v osc</td>
<td></td>
</tr>
<tr>
<td>KM3NET/ARCA</td>
<td>Mediter.</td>
<td>C</td>
<td>1.2 GT</td>
<td>10 GeV</td>
<td>WC</td>
<td>v astr</td>
<td></td>
</tr>
<tr>
<td>JUNO</td>
<td>China</td>
<td>C</td>
<td>20 kT</td>
<td>1 MeV</td>
<td>LS</td>
<td>Rv osc</td>
<td></td>
</tr>
<tr>
<td>INO</td>
<td>India</td>
<td>T</td>
<td>50 kT</td>
<td>600 MeV</td>
<td>Fe</td>
<td>Atm v</td>
<td></td>
</tr>
<tr>
<td>P-ONE</td>
<td>Pacific-Canada</td>
<td>C</td>
<td>1 km² ?</td>
<td>GeV ??</td>
<td>WC</td>
<td>v astr</td>
<td></td>
</tr>
</tbody>
</table>
Key for previous tables comparing projects:
st = status
P = proposal
C = construction
T = testing
O = R = operating
X = no longer operating
R>X = O>X soon shutting down
Area/vol = muon effective area or target volume/mass, very rough measure
and generally energy dependent
dΩ = observing solid angle
Energy = rough neutrino energy threshold
Tech = detection technology
AC = Air Cherenkov
IC = Ice Cherenkov
WC = Water Cherenkov
HWC = Heavy Water Cherenkov
IR = Ice Radio
ICR = Ice Cherenkov Radio
LS = liquid scintillator
AR = Air Radio
Fe = Iron Calorimeter
ν astr = Neutrino Astronomy
ν osc = Neutrino Oscillation Studies
Rν osc = Reactor Neutrino Oscillation Studies
PDK = Proton Decay Search
geov = mainly geo-neutrino studies

Please let me know about errors and omissions!

With much help from Christian Spiering
OK, where are we and where are we going soon with neutrinos?

At lower energies (<TeV) we have found neutrino oscillations and mass and much more about neutrinos... amazing experimental results

~ lifetime, they make it from distant objects at ~c
~ standard model cross sections, but >EeV quite uncertain
~ 3 families and weak hints of more (revolution if so)
~ mixing angles curiously larger than for quarks, forget Cabibbo
~ mass trending towards $m_1 < m_2 < m_3$ as with quarks, but why?
~ unclear about CP violation (but really so what, RH nus?)
~ some peculiarities in nuclear reactor nu expts (RNA and 5 MeV bump)
~ solar models and atm nu fluxes ~ OK (to 15% or so!)
~ no observation of expected Direct Production (OK?)

And still no theory guidance from a grand scale GUT

Still we know very little more about cosmic rays and sources > PeV
Review of opportunities for natural neutrinos by energy:

- **Big Bang Relics**: No good ideas out there… biggest challenge, only indirect inferences
- **Pre-white dwarves**: Dominant radiation in neutrinos but keV energies, no flux calcs
- **<MeV Geo neutrinos**: particularly K40, important challenge
- **Relic SN Neutrinos**: in few MeV range, maybe in reach of HyperK
- **Galactic SN**: 10’s of MeV… few/century, could be any time
- **Atmospheric Neutrinos**: 100 MeV to >TeV, continue to be a gold mine for nu properties
- **Few TeV from mostly galactic sources**: IceCube now, others follow
- **<100 TeV astro nus**: could yield wonderful surprises, IC in progress
- **1-10PeV**: as now seen in IC: the promised land and probably most fruitful in ~10 yrs
- **Glashow ~6.4 PeV and Double Bang**: astro nu flavors coming, slowly
- **EeV**: Where are the BZ neutrinos?
- **And what are those ANITA events?** This is indeed *terra incognita*
Focusing on UHE Astro Neutrinos

Below PeV optical detectors will continue to dominate, but current IceCube and others not big enough to move ahead

In the range of PeV -> EeV we clearly need help from

**New Detectors** and

**New Techniques**

Above PeV, due to $E^2$ scaling **Radio** and maybe **Acoustic** will come to the fore
conclusion

• After half a century of dreaming, exploration and development, and now great activity

• we are seeing the Promised Land, we have a glimpse of HE Neutrino Astronomy

• It is sparse but we know how far we must go...
  Need ~100 km3 for the high energies!

• The mysteries of neutrino behavior and the sources of the most energetic events in the universe remain enigmatic, but within grasp

• You can bet on surprises!
Some Advice for Ocean Neutrino Hunters

some controversial from jgl experiences (random order)

• First off plan to test, test, test and in-ocean!
• Connectors are the bane of our experiments… source of most failures.
• Experienced Physicists should be overall involved in the design details, not handing over to engineers.
• Avoid review committees without ocean experience!
• Unlike IceCube, design for service and reconfiguration.
• Buy all possible components, from proven mfrs.
• Reprogrammable software in ocean.
• More than one data link to shore, no single point fail.
• In the past, large stupid light collectors always won. Now?
• Beware stored charge in HV ocean cables… Total power an issue.
• Neutrino induced showers, not muons, are your future.
• Work on shower directionality reconstruction to go beyond IC.
• Plan for eventual ~10 KM³
Special Opportunity:
Incorporate MeV Neutrino Detector

- OceanBottomKamLAND stirring in Japan
- 10-50 KT closed detector of Geonus, and more
- Can be deployed with help of huge Japanese Chikyu drill ship, connected to Neptune?
- P-ONE forms giant trigger/veto
- Much like IceCube with dense core, but better!
- Much synergy between OBK and P-ONE.
- I hope we can start useful discussions with you all and colleagues at Tohoku U (Kamland)/
• This looks to be a grand adventure and I send best wishes for rapid advancement.
• I hope we can work out means for some possible UH participation,
• and for linking to the budding OBK in Japan
• Have an exciting meeting!