Neutrino Astronomy…
Particle Physics with a Petaton

David Saltzberg (UCLA),  SLAC SUMMER INSTITUTE LECTURE,  AUGUST 2008
One Motivation for a Particle Physicist

- **Exotic Physics**: UHECR would result from decays of super-heavy particles.
- **Example**: Grand Unified Supersymmetric Theories:

  - Is its lifetime comparable to age of universe or is it $\sim 10^{-40}$ sec?
  - Loophole—produce them continuously by “topological defects” (TD)
…for a particle physicist
Livingston Plot

(E_{CM} (GZK) \sim 150 \text{ TeV})

How do we re-enter this region?
Enhancement of UHE Neutrino Cross Section

Sample predictions for TeV scale quantum gravity

- UHE $\nu$ cross sections could be up to $\sim 100\times$ Standard Model
  * would be invisible to UHECR interactions
Measuring $\nu$ cross section up to $E_{CM}=150$ TeV

- 30% Cross Section measurement with ground detector easily achievable using Earth as a filter near horizon.
- Not dependent on GZK shape or absolute intensity.
- Angular resolution even for non-contained events is sufficient.
- Anomalous cross sections from large extra dimensions etc. at $E_{cm}=150$ TeV would be clearly visible.
More Particle Physics:
\( z=1 \) is a VERY long baseline

- One experimental parameter: \( (L/E)_{\text{experiment}} \propto t^\nu_{\text{proper}} \)
  - Determines (largely) the sensitivity to
    - \( \Delta m^2 \), decays (eg majoron emission) decoherence ...

Order of magnitude:

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

Particle Physics in Neutrino Sector

- GZK neutrinos are the “longest baseline” neutrino experiment:
  - Longest L/E (proper time) for: extra $\nu$ admixtures & anomalous $\nu$ decays
  - SUN: L/E $\sim$ 30 m/eV
  - GZK: L/E $\sim$ 10$^9$ m/eV

- Measured flavor ratios of $\nu_e : \nu_\mu : \nu_\tau$ can identify non-standard physics at source

$\nu_e : \nu_\mu : \nu_\tau \rightarrow (5-6):1:1$

Neutrino decay leaves a strong imprint on flavor ratios at Earth
If local enhancement of local CNB:

\[ \sqrt{2m^{\text{CNB}}_\nu E^{\text{UHECR}}_\nu} = M_Z \sim 10^{11} \text{ eV} \]

if \( m^{\text{CNB}}_\nu \sim 0.05 - 0.5 \text{ eV} \)

\[ \Rightarrow E_\nu \sim 10^{22} - 23 \text{ eV} \]

\[ \Rightarrow \text{Would be a minimum flux of } 10^{23} \text{ eV neutrinos} \]
Z-burst neutrino mass spectroscopy of CNB

Barenboim, Requejo, Quigg, PRD71,083002 (2005)
Three Good ideas by Gurgen Askaryan
(1928-1997)

How to go beyond 10 km$^3$ neutrino detector?

Optical attenuation/scattering lengths $\sim 100$ m
km³ and Beyond?
Three Good Ideas by Gurgen Askaryan (I)  
(1962)

UHE event will induce an e/γ shower:

In electron-gamma shower in matter, there will be 
~20% more electrons than positrons.

Compton scattering:  \( \gamma + e^-_{\text{(at rest)}} \rightarrow \gamma + e^- \)

Positron annihilation:  \( e^+ + e^-_{\text{(at rest)}} \rightarrow \gamma + \gamma \)
Three Good Ideas by Gurgen Askaryan

Excess charge moving faster than $\frac{c}{n}$ in matter emit Cherenkov Radiation

$$\frac{dP_{CR}}{d\nu} \propto \nu \, d\nu$$

Each charge emits field $|E| \propto e^{i k \cdot r}$ and Power $\propto |E_{tot}|^2$

In dense material $R_{\text{Moliere}} \sim 10\text{cm}$.

$\lambda \ll R_{\text{Moliere}}$ (optical case), random phases $\Rightarrow P \propto N$

$\lambda \gg R_{\text{Moliere}}$ (microwaves), coherent $\Rightarrow P \propto N^2$

Confirmed with Modern simulations + Maxwell’s equations:
(Halzen, Zas, Stanev, Alvarez-Muniz, Seckel, Razzaque, Buniy, Ralston, McKay …)

Optical viewing $\sim 100\text{m}$, Radio viewing $\sim 1\text{km}$
Three Good Ideas by G. Askaryan (1962)

- #3. Can exploit this effect in large natural volumes transparent to radio (dry):
  - pure ice, salt formations, lunar regolith
  - eg, “RICE” experiment

- ***Other ideas by Askaryan:
  - Bubble chamber
  - Laser Ablation
  - Laser self-focussing
  - Acoustic UHECR detection ...
The SLAC `"Kitty Litter" box

4 tons sand

● Amplitude expected
● 100% linearly polarized
● Cherenkov angle
South Pole Ice properties: RF attenuation

Radio Echo measurements
Amundsen–Scott Station
S. Barwick et al. 2004

Average attenuation to 1200m depth
mean T= -45°C
Errorbars show ~2 σ systematics
Thermal Fluctuations

Black Body Fluctuations:

freq>>peak:

\[ \delta(N_\gamma) = \sqrt{N_\gamma} \]

“shot noise”

freq<<peak:

\[ \delta(N_\gamma) = N_\gamma \]

S-band obs. of moon (far below peak)

V is Gaussian with \[ \sigma = \text{r.m.s.}(V) \]
Using the Moon as a 200,000 km$^3$ Target

- Zheleznyk and Dagkesamanskii (1988)
  - $10^{20}$ eV $\nu$ produces $\sim$1000 Jy at 2GHz
    - (1Jy = $10^{-26}$ W/m$^2$/Hz)
  - brightest quasars $\sim$25 Jy at this frequency band
  - Moon as blackbody: $\sim$200 Jy
    - no need to go to the moon
    - use radiotelescopes

12 hrs using single Parkes 64m dish in Australia (1996)
Limitted by R.F.I.

Goldstone Lunar UHE Neutrino Search (GLUE)

P. Gorham et al., PRL 93, 041101 (2004)

Two antennas at JPL’s Goldstone, Calif. Tracking Station

- limits on $>10^{20}$ eV $\nu$’s
- regolith atten. len. $\sim$20 m
- $\sim$123 hours livetime
- $[V \Delta \Omega]_{\text{eff}} \sim 600$ km$^3$-sr

New experiment planned using Westerbork (NL) Antennas
A more detailed view of GLUE (since common to most radio detection)
• “Radio in Ice Experiment”

• Dipoles (250-1000 MHz) on AMANDA strings @ S Pole

• 200 x 200 x 200 meter array

• $E_{\nu} > \sim 10^{17}$ eV

• $[V\Delta\Omega] \sim 10 \text{ km}^3\text{-sr}$

NEW 7 year result Kravchenko, et al., PRD73,082002
>100 km Cherenkov Ring in Air

ANITA simulated event
FORTE satellite
(Fast On-orbit Recording of Transient Events)

- Main mission: lightning
- Viewed Greenland ice with appropriate trigger (1997-99)
  - 1.9 MILLION km³
  - 38 days at 6%
- Can self-trigger on transient events in 22MHz band in VHF band (from 30 to 300 MHz)
- Event characterization
  - polarization
  - ionospheric group delay and birefringence
  - timing

N. Lehtinen et al., PRD 69, 013008 (2004)
Example Forte Event

- $E_v^{\text{thresh}} \sim 10^{22}$ eV
- $[V\Delta\Omega] \sim 100,000 \text{ km}^3 \text{ sr}$, but threshold extremely high.
>1 million cubic km!
Plan 60 days in 3 flights
$E_\nu > 10^{17} \text{ eV}$
$[V\Delta\Omega] \sim 20,000 \text{ km}^3\text{-sr}$
ANITA World Tour

- **December: 2003-04** Anita-lite
- **June 2005** Test run at Ft. Sumner, NM
- **June 2006** Full ANITA assembled
- **June 2006** Testbeam with Ice target @SLAC
- **July 2006** shipped to the ice...
- **Dec 06-Jan 07** Flight!

photo: Jeff Kowalski
Anita collaboration list available online
Historic LDB Flight Paths

East Antarctica= Deepest Coldest Clearest Ice
ANITA flight

- 35 Days
- Second longest LDB flight
- Away from bases, saw thermal noise levels.
AURA & IceRay: Expanding Ice-Cube Hybrid Acoustic & Radio Techniques

from J. Kelly presentation
ARIANNA: 100 x 100 station Array

Ross Ice Shelf, Antarctica
SALSA:
A possible salt detector

- ~25km³ in upper 3km of dome (75 km³ water-equiv.)
  - >2λ denser than ice
  - easier to deploy than S.Pole

- Calorimetric; large V, ∆Ω; Cherenkov polarization usable for tracking

- Good candidates in Texas and Louisiana, maybe Utah

diapir action pushes out water

~1km³ w.e.
SalSA simulations

- A 2.5 km³ array with 225 m spacing, 12²=144 strings, 12³=1728 antenna nodes, 12 antennas per node, dual polarization  ==>  $V_{\text{eff}} \Omega \approx 400 \text{ km}^3 \text{ sr w.e. at 1 EeV}$

- Threshold $<10^{17}$ eV, few 100s antennas hit at 1 EeV, >1000 hits at 10 EeV

- Rate: at least 20 events per year from rock-bottom minimal GZK predictions
Cote Blanche Salt Attenuation Lengths

Fig. 1.

Field Attenuation Length (m)

Frequency (GHz)
Another Good Idea from Askaryan (III): Acoustic Detection
(1957)

Verified in beamtests at Brookhaven (J. Learned)
SAUND
(Study of Acoustic Underwater Neutrino Detection)

- 7 Hyrdophones, subset U.S. Navy array (AUTEC)
- Detection 7kHz to 50 kHz
- Noise floor $\nu^{-1.7}$, sets threshold $\sim 10^{23}$ eV
- Physics run 195 days

J. Vandenbrouke et al., Ap. J. 621, 301
SAUND Calibration

- $E \nu \sim 10^{22} \text{ eV}$: too high for now.

  but salt domes may prove

  $10 \times$ more signal and much

  less background
Acorvē

- Poster by your classmate, Simon!
- Array of Rona 8 hydrophones off of coast of Scotland
- Monitor at 140 kHz, digitize all
- No up-front hardware trigger needed.
Other Developing(?) Ideas

- Drone flights over deepest Antarctic Ice or
- View from a Mountainside
  - use the best ice: up to 4km deep
  - closer ➔ lower threshold
  - instrument can be maintained
  - 1 year/ year
- ANITA++
  - Phased array of balloon-borne deployable antennas
- Lunar or even Europa orbiter
  
  There are more ideas than people to work on them
Reaching GZK sensitivity & Lowering the Threshold

Events! even if UHECR are Iron

limits are for energy bin with $E_{\text{hi}}/E_{\text{lo}}=e$
Where we might be in just 2 years…

- **IceCube**
  - Discovery of bottom-up sources
  - Discovery of a few GZK neutrinos

- **ANITA**
  - Discovery of a handful of GZK neutrinos

- **Auger**
  - Discovery of a few GZK neutrinos?
GZK Neutrinos are coming....Are you ready?

- Conclusion-II (for a particle physicist):
  - UHE $\nu$ may provide an HEP laboratory:
    - Probe total cross section & new physics at highest $E_{cm}$
    - The longest baseline available neutrinos– by far
“Enough storyboarding. Let’s shoot something.”