Particle Physics Opportunities

with the Next Generation
Ultra High Energy Neutrino Telescopes

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Particle Physics with a Tevatron

Teraton
Astrophysical Neutrino Sources
“Batting 1000”

ν weak eigenstates ≠ mass eigenstates
ν mass

dispersion → ν mass limits
constrains ν decay scenarios
Conclusion

- **Saltbed Sensor Array: Overview**
  - Instrument 1000-km$^3$–sr neutrino aperture
  - Use radio emission from neutrino induced showers:
    - 10 times the attenuation length of water & ice

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Halite (rock salt)
- $L_\alpha(<1\text{GHz}) > 500$ m w.e.
- Depth to $>10$ km
- Diameter: 3-8 km
- $V_{\text{eff}} \sim 100$-200 km$^3$ w.e.
- No known background
- $>2\pi$ steradians possible
GUT scale particles

- **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**” remaining from Big Bang
Topological Defects

- Some specific models
  - Bhattacharjee, Hill, Schramm PRL 69, 567, (1992)
  - Protheroe & Stanev PRL 77, 3708 (1996)

- Basic ideas
  - Were attractive to circumvent GZK cutoff for UHE cosmic rays.
  - Topological defects could be monopoles, superconducting cosmic strings, domain walls
  - Generally these models produce hard neutrino spectrum: \( \sim E^{-(1-1.5)} \)
    - “bottom-up” scenarios are more steeply falling: \( E^{-2} \) to \( E^{-4} \)
    - not ruled out by lower energy telescopes
    - constrained by MeV—GeV isotropic photon fluxes
  - Neutrino flux vs. energy sensitive to source evolution vs. \( z \) of TD’s.
“Guaranteed” Neutrinos

Astrophysical processes are producing particles over at least 7 more orders of magnitude

Neutrinos would point back:

- Sources may produce neutrinos directly
- or indirectly ("GZK process")

\[ p + \gamma_{2.7K} \rightarrow \Delta^* \rightarrow n + \pi^\pm \]

“guaranteed” neutrinos
Summary UHE ν Models

\[
\text{intensity (} I \text{)} = \frac{d^3N}{dA d\Omega dt}
\]

\[
\text{brightness (} I_E \text{)} = \frac{d^4N}{dA d\Omega dt dE}
\]

- Possible point of confusion:
  - Models give brightness
  - But, experiments measure intensity
Most commonly used:
**B&B physics with $\nu$ cross section**

- HERA tests proton structure to $x \sim 10^{-4}$ (only $10^{-2}$ at “high” $Q^2$)
- UHE $\nu$ probes proton structure to $x \sim 10^{-8}$
- Extreme regime: More likely to scatter off of bottom sea than up/down valence.
- observables?
- Check SM with NC/CC ratio at extremely high $Q^2$
UHE Neutrino Cross Section and low-scale Quantum Gravity

- Probing interactions at high CM
  - $E_{\text{cm}} = \sqrt{2m_p E_\nu^2} \Rightarrow 150 \text{ TeV for } E_\nu = 10^{19} \text{ eV}$
  - $\sigma_{\text{SM}}(\nu+N) \sim 10^{-7} \varepsilon \sigma_{\text{SM}}(p+N)$

- Large extra dimension models could enhance $\nu$ cross section
  - Gravity could become strong at $E_{\text{CM}}=M_D$
  - Non-perturbative effects could produce KK-exitations, string excitation, p-branes, micro-BH above $E_{\text{CM}}$

$$M_D = \left[ \frac{M_{pl}^2}{8\pi r_C^n} \right]^{2/n} \text{ where } M_{pl} \equiv 10^{28} \text{ eV}$$

- Astrophysics and laboratory limits still allow
  - $n=4, M_D > 10$ TeV
  - $n \geq 5, M_D > 1$ TeV
Enhancement of UHE Neutrino Cross Section

Sample predictions for \( M_D \sim 1 \text{ TeV}, n \sim 6-7:\)

- Caveat: not all energy goes into BH or excitation, and need minimum energy for classical BH formation.
- UHE \( \nu \) cross sections could be up to \( \sim 100 \times \) Standard Model
  * would be invisible to UHECR interactions
Neutrino Telescopes for Direct Monopole Detection

**Monopoles:**
- Dirac: The presence of even one monopole explains electric charge quantization
- Masses typically of order GUT scale
- but in some models $M_{mp}$ could even be as low as $\sim 10^{14}$ eV.
- $E$ in extra-gal. magnetic fields $\sim 10^{24}$ eV

**Parker bound** ($10^{-15}$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$)
- c.f. UHECR$>10^{20}$ eV ($\sim 10^{-21}$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$)
- other direct MP searches barely approach Parker bound
- Caveat: if monopoles catalyze proton decay then (lack of) neutron star heating provides extremely strong limit.
Neutrino Telescopes for Direct Monopole Detection

Wick, Kephart, Weiler, Biermann

- Relativistic monopoles mimic particle with large charge: at least $Z \sim 68$
  - produce EM showers along path by pair-production, photo-nuclear
  - continuously produces shower along its path $\rightarrow$ unique signature
- WKW estimate $F < 10^{-18} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ for a km$^3$ detector for 1 year.
  - SalSA could do $\sim$10-100 times better:
    - sensitive for $M_{mp}$ up to $10^{23}$ eV, far beyond production at accelerators.
    - Flux limit better than typical searches
Anomalous Neutrino Decay

- Critical parameter for neutrino oscillations and decay is proper time, \( L/E \).
  - Solar neutrinos: \( 150,000 \text{ km/}5\times10^6 \text{ eV} = 30 \text{ m/eV} \)
  - “SalSA” neutrinos from 4 Gpc/\(10^{17} \text{ eV} = 10^9 \text{ m/eV} \)
- No SM \( \nu \) decay from SM on these time scales
  - However, \( \nu \rightarrow \nu + J \) (J= Majoran)
  - Flavor ratios would be from lightest mass eigenstate

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"Normal" hierarchy

\[
\Delta m_{23}^2 \quad \begin{cases} \mu \mu \tau \\
\text{(atm.)} \\
\Delta m_{12}^2 \quad \begin{cases} e\mu \tau \\
\text{(solar)} 
\end{cases}
\end{cases}
\]

- Beacom, Bell, Hooper, Pakvasa, Weiler
  - \( \nu_e : \nu_\mu : \nu_\tau \)
  - \( \sim 1:1:1 \) ! 5:1:1
Beyond km$^3$?  
Two Good Ideas by Gurgen Askaryan (I)  
(1962)

UHE event will induce an e/$\gamma$ shower:

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

Compton scattering: $\gamma + e^-_{(at \ rest)} \rightarrow \gamma + e^-$
Positron annihilation: $e^+ + e^-_{(at \ rest)} \rightarrow \gamma + \gamma$
Two Good Ideas by Gurgen Askaryan (I)

Excess charge moving faster than \( c/n \) in matter emit **Cherenkov** Radiation

\[
\frac{dP_{CR}}{d\nu} \propto \nu d\nu
\]

Each charge emits field \( |E| \propto e^{ikr} \)

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 …)
Another Good Idea from Askaryan (II):
Acoustic Detection
(1957)

- Verified in beamtests at Brookhaven (J. Learned, L. Sulak…)

![Diagram of acoustic detection in ocean water with a hydrophone and pressure vs. time graph.](image)
The SLAC Salt and Sand boxes

- Amplitude expected
- 100% linearly polarized
- Cherenkov angle
RICE Experiment

- “Radio in Ice Experiment”
- Dipoles (100-1000 MHz) on AMANDA strings @ South Pole
- 200 x 200 x 200 meter array
- Uses long attenuation length (view to ~ 7km)
- \( E_\nu > 10^{17} \) eV
- \([V\Delta\Omega] \gg 10^{\text{km}^3\cdot\text{sr}}\)
- Status
  - published on 333 hour dataset
  - results from 3-year dataset
  - datataking ongoing
- Expected events in 5 years:
  - ~9 TD events
  - 2-7 GZK events
  - ~3 GRB/AGN events

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 attenu. len. \(\sim 20\) m
- \(\sim 123\) hours livetime
- \([V\Delta\Omega]_{eff} \sim 600\) km\(^3\)-sr
- datataking complete

Example Forte Event

$E_v^{\text{thresh}} \gg 10^{22}$ eV

$[V\Delta\Omega] \sim 100,000 \text{ km}^3 \text{ sr}$, but threshold extremely high.
ANITA

$E_\nu > 10^{17}$ eV

$[V\Delta \Omega] \sim 20,000 \text{ km}^3\text{-sr}$

First flight in 2006-07

Anita-LITE

- 18 day flight in 2003-04
- Antarctica proved very radio quiet
- Observed the Sun as calibration
- Ground pulses observed w/120 psec timing – gives $\delta \phi = 2^\pm$, $\delta \theta = 0.5^\pm$
## Comparing using Models

<table>
<thead>
<tr>
<th>Telescope</th>
<th>Duration</th>
<th>$N_{\text{events}}$</th>
<th>Top. Def.</th>
<th>GZK</th>
<th>WB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anita</td>
<td>45 live days</td>
<td>43</td>
<td>(PS)</td>
<td>4.8</td>
<td>18</td>
</tr>
<tr>
<td>Amanda B10</td>
<td>130 live days</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Auger</td>
<td>3 live years</td>
<td>0.7</td>
<td>(min)</td>
<td>1.0</td>
<td>3.0</td>
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<tr>
<td>EAS-TOP</td>
<td>326 live days</td>
<td>-</td>
<td>(max)</td>
<td>-</td>
<td>-</td>
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<tr>
<td>Euso</td>
<td>2.7 live years</td>
<td>18</td>
<td></td>
<td>0.9</td>
<td>3.6</td>
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<td>80 hours</td>
<td>0.11</td>
<td></td>
<td>-</td>
<td>0.011</td>
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<tr>
<td>Ice Cube</td>
<td>3 live years</td>
<td>1.1</td>
<td></td>
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<td>-</td>
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<td>-</td>
<td>-</td>
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<tr>
<td>Rice</td>
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<td>2.7</td>
<td></td>
<td>0.7</td>
<td>2.3</td>
</tr>
<tr>
<td>Salsa</td>
<td>2 live years</td>
<td>34</td>
<td></td>
<td>39</td>
<td>130</td>
</tr>
</tbody>
</table>
SalSA: A Next Generation UHE neutrino detector

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

- Many competing effects make it not obvious which frequency is optimal:
  - attenuation, antenna effective height, Ch. emission formula, Ch. cone width, bandwidth, thermal noise
  - Monte Carlo used to study these events

- As long as attenuation length is smaller than dome, then optimum at longer wavelengths

- Calorimetric; large V,$\Delta \Omega$; Cherenkov polarization usable for tracking

- US likely TX or LA. Dutch investigating sites as well

Diapir action pushes out water
Salt Attenuation

*Need to confirm with more sensitive attenuation length measurements*

*Measurements so far, consistent with 300K thermal noise*
Simulated Events

Shower energy = $10^{19}$ eV  

Neutrino direction: alt = 8°, az = 134°

alt = 28°, az = 239°

alt = 28°, az = 149°

alt = 28°, az = 59°

alt = 68°, az = 149°
Acoustic Detection

- **SAUND**  J. Vandenbrouke et al., astro-ph/0406105
  - 7 Hydophones, subset U.S. Navy array (AUTEC)
  - Detection 7kHz to 50 kHz
  - Noise floor sets threshold $\sim 10^{23}$ eV
  - Reason to believe Salt detector will have lower threshold. Studies underway.
  - Possibility to detect events in salt with BOTH acoustic and radio. Relative timing gives extra distance handle
Roadmap for the Next Generation Salt Detector

- Have exhausted easy measurements
- Need to drill 5-7 boreholes in candidate salt domes
  - measure ambient noise
  - measure attenuation lengths
  - prototype sensors, triggering, readout
  - proposal forming for $2-5M to accomplish this in next 1-3 years
- Use data from R&D study
  - Be ready with full proposal when Anita, Auger, IceCube discover GZK neutrinos in the next 2-4 years
Conclusions
(for a particle physicist)

- Current generation of UHE $\nu$ telescopes will likely detect GZK-induced neutrinos in next 2-4 years
- Need to be prepared for this “beam” as particle physicists
  - Measure neutrino cross section
    - extreme proton structure
    - test for large-scale quantum gravity
  - Aperture for magnetic monopoles
    - best sensitivity for $\beta \sim 1$.
  - Anomalous neutrino decay (e.g., majorons)
    - Best L/E sensitivity. Measure flavor ratios.
- Large Salt Domes offer the possibility to turn the detection of a few GZK neutrinos into a sample of 100’s of events.
  - site selection, prototype arrays need to start soon
• Conclusion-II  (for an astronomer):
Backup Slides
Comparison of Detector Discovery Potential: $[\Delta \Omega] \mathcal{E} \Delta t_{\text{live}}$

$\nu_e + \nu_\mu + \nu_\tau$ (Area * Steradians * Livetime$)/N_{90}$

(Some current, others projected)

- These are for 90%CL detection (i.e., divided by 2.3 if no bckgd)
- Only radio & acoustic limits currently above $10^{16}$ eV
- Will update a little for proceedings

Plots for other flavors etc. at http://www.physics.ucla.edu/~saltzbrg/uhenu.ps
Quantifying Detection

- \([A \Delta \Omega] \Delta t\) vs. energy (\& background) for each neutrino flavor describes experiment
  
  \[ N_{obs} = \int I_E \times [A\Delta\Omega] \ dA d\Omega dEdt \]

  - For example: \([A \Delta \Omega]\) for a flat, black paddle = \(A\pi 2\pi\)
  - \([V \Delta \Omega] = [A \Delta \Omega] L_{int}\) accounting for neutrino cross section vs. energy
  - (Discovery potential also depends on background)

- Need many km\(^3\) of material to detect \(> 10^{15}\) eV

- Here I’ll give (my estimates of):
  
  - \(E_\nu^{\text{thresh}}\) (approx.)
  - typical \([V \Delta \Omega]\) and \(\Delta t\)
  - Compare at the end with \([A \Delta \Omega] \Delta t\) for detection
Z-bursts?

If local enhancement of local CNB:

\[ \sqrt{2m_{\nu}^{\text{CNB}} E_{\nu}^{\text{UHECR}}} = M_Z \sim 10^{11} \text{eV} \]

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

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

\[ \Rightarrow \text{Would be a minimum flux of } 10^{23} \text{ eV neutrinos} \]
Astrophysics Motivations:
The range of photon astronomy

Radio Astronomy
<10^{-7} \text{ eV photons}

Atmospheric Cherenkov
>10^{12} \text{ eV photons}

...and everything in between
The end of photon astronomy

- No Extra-galactic photon astronomy beyond $\sim 10^{14}$ eV

- No cutoffs for neutrinos

Distance to M32

\[ \gamma^+ \gamma_{IR} \rightarrow e^+ + e^- \]

\[ \gamma^+ \gamma_{URB} \rightarrow e^+ + e^- \]
Beyond $10^{14}$ eV?

Astrophysical processes are producing particles over at least 7 more orders of magnitude.

Sources are still a mystery:

AGN, GRBs?

- could produce $\sim 1/E^2$ neutrino flux

Neutrinos would point back:

- Sources may produce neutrinos directly
- or indirectly ("GZK process")

$$p + \gamma_{2.7K} \rightarrow \Delta^* \rightarrow n + \pi^\pm$$

"guaranteed" neutrinos
How to instrument more than a few $\text{km}^3$ –sr?

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“guaranteed” neutrinos
A more detailed view of GLUE (since common to most radio detection)
SAUND Calibration

\[ \sim 10^{21} \text{ eV!} \]

- Attenuation length >500-1000m
Developing Ideas

- Drone flights over deepest Antarctic Ice
  - use the best ice: 4km deep
  - closer ➔ lower threshold
  - instrument can be maintained

- Europa orbiter

Stay Tuned…
Other Acoustic Efforts
(Acoustic workshop Sept ’03)

- SADCO: Black Sea Oil Platforms and Kamchatka
- Hockley/Oakwood Domes. (Measurements begun)
- Europe
  - Mediterranean: Nemo, Antares
  - European Salt domes
  - Rona UK
- PZT sensors on Amanda under study

Summary slides at
Some on-board impulsive noise, will be removed for dedicated ANITA flight.

No evidence for off-payload impulsive noise beyond McMurdo Station horizon.
Anita Lite
Resolutions

Ground-to-payload pulse at ~250km
from Williams’ Field

375 MHz “tone burst”

Anita goal 300ps per antenna
Anita-lite already 120 psec

- Anita resolution on RF direction
  \[ \delta \theta > 0.5^{\pm} \]
  \[ \delta \phi > 2^{\pm} \]
SAUND
Neutrino Search

$E_\nu \sim 10^{22}$ eV

$[V \Delta \Omega] \sim 100$ km$^3$-sr

Not enough…

but salt domes may prove 10£ more signal and much less background
FORTE satellite
(Fast On-orbit Recording of Transient Events)

- Main mission: synaptic lightning observation
- Viewed Greenland ice with appropriate trigger (1997-99)
  - 1.9 MILLION km³
  - 38 days £ 6%
- Can self-trigger on transient events 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)
Salt Dome Detector
Noise and attenuation length measurements

P. Gorham et al., NIMA 490, 476 (2002)

- Attenuation >250m (>500 m w.e.)
  (even at 750 MHz)
- No evidence of birefringence or scattering
- RF environment protected by overburden. Noise level consistent with 300K.

- Estimated events/year
  - $100 \, R_X \implies 50/yr \text{ above } 10^{17} \text{ eV from AGN}$
  - $1000 \, R_X \implies 50/yr \text{ above } 10^{17} \text{ eV from GZK or 5-10 GRB}$