Particle Physics Opportunities with the Next Generation Ultra High Energy Neutrino Telescopes

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“The Highest Energy Physics”
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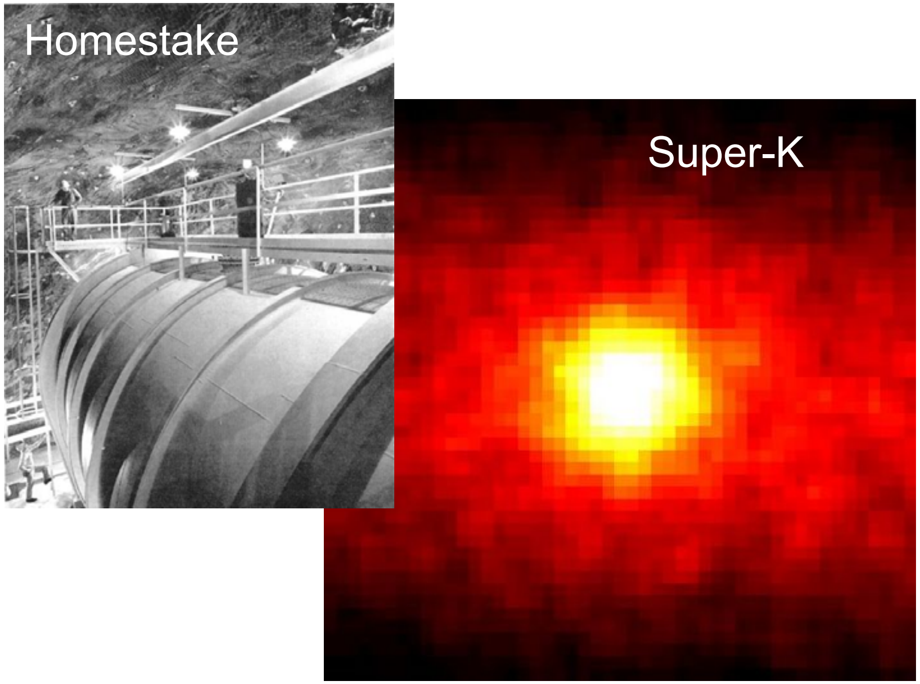
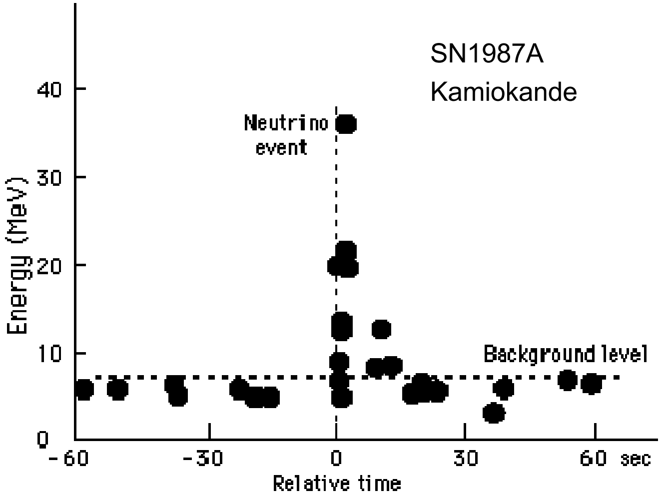
Particle Physics with a Te~~va~~tron

Teraton

Astrophysical Neutrino Sources
“Batting 1000”



ν weak eigenstates ≠ mass eigenstates
ν mass

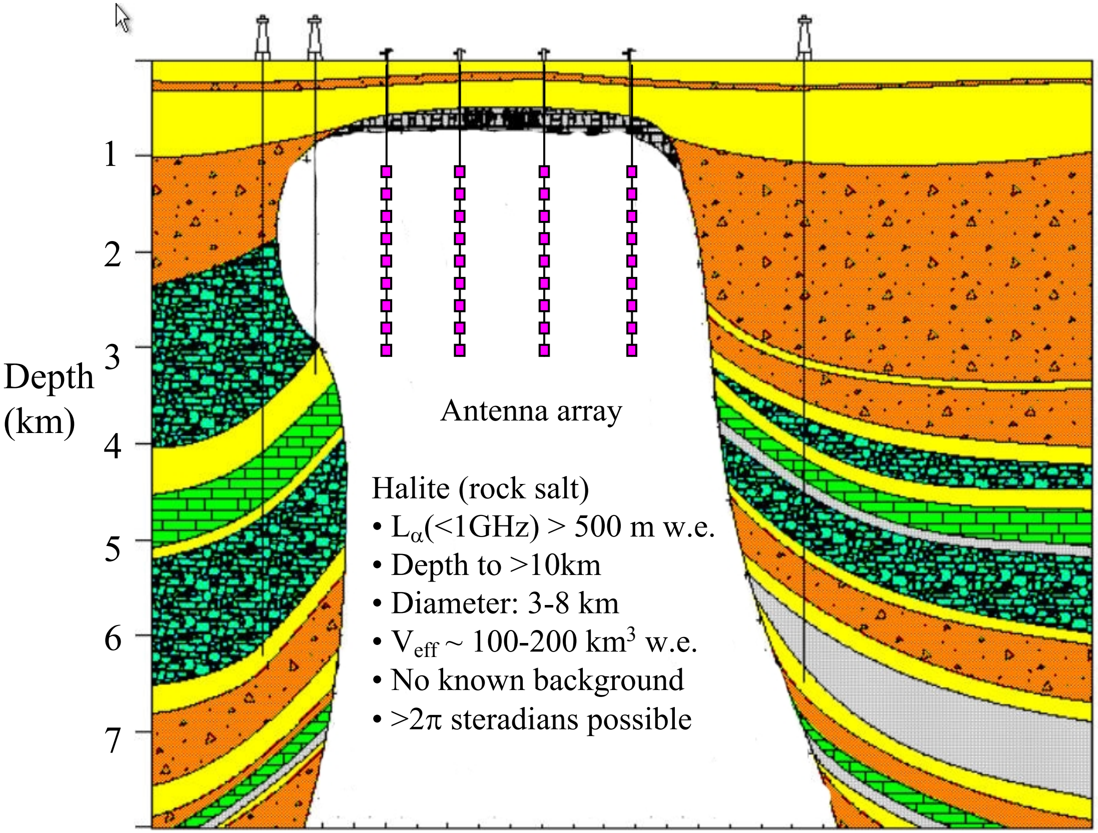


dispersion ➔ ν mass limits

constrains ν decay scenarios

Conclusion

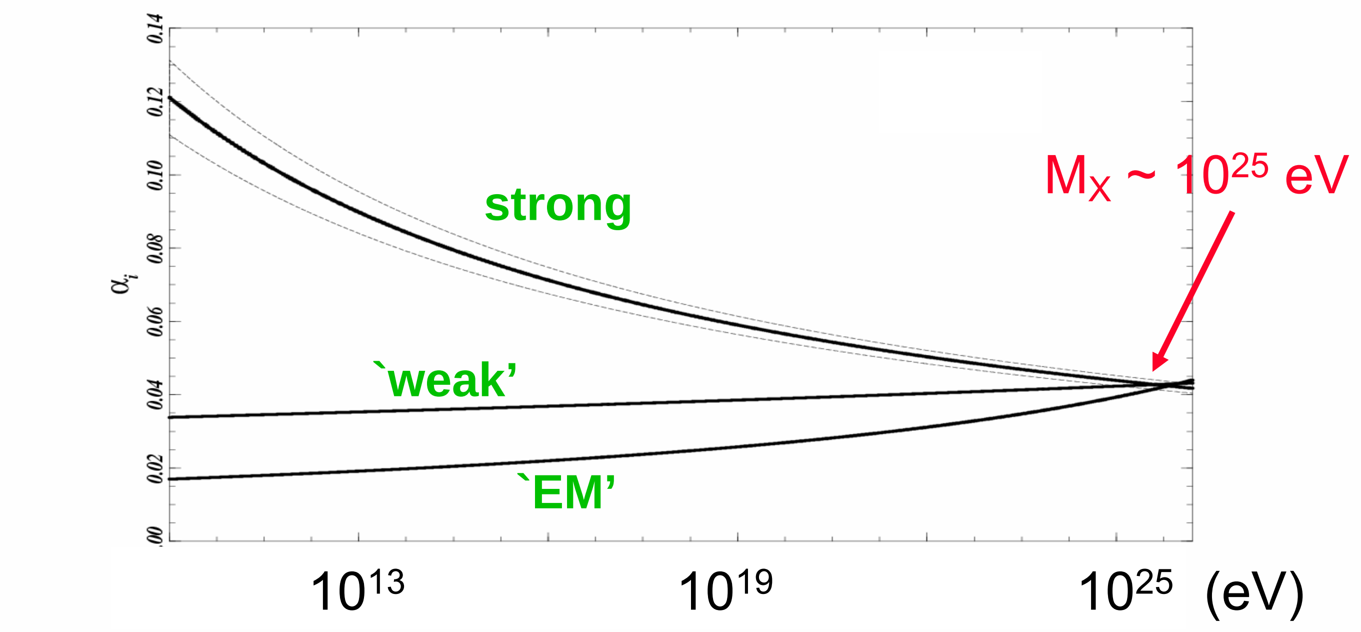
- Saltbed Sensor Array: Overview
  - Instrument 1000-km^3 –sr neutrino aperture
  - Use radio emission from neutrino induced showers:
    - 10 times the attenuation length of water & ice



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

GUT scale particles

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



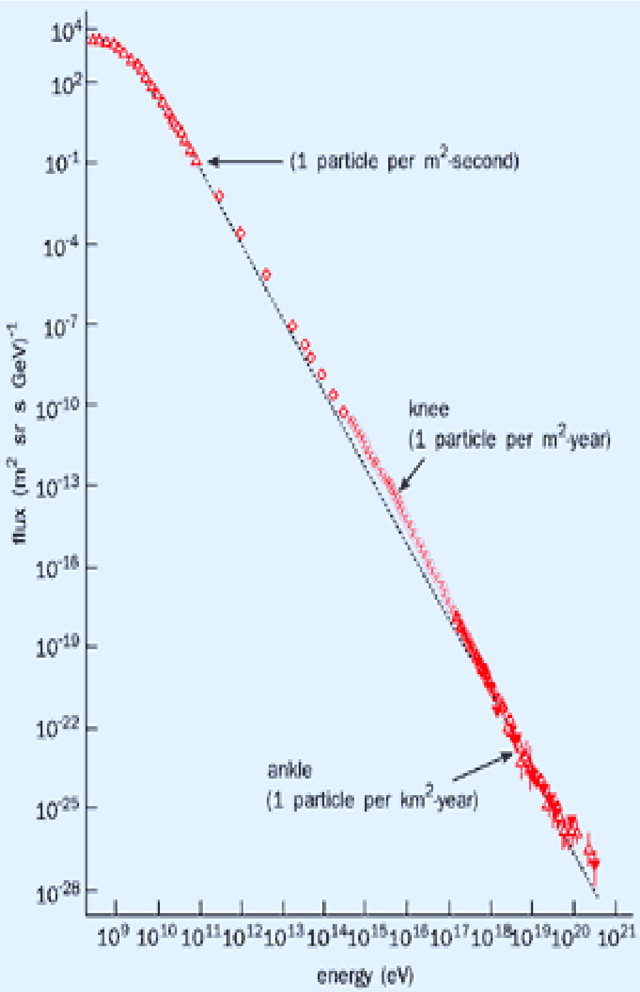
Is its lifetime comparable to age of universe or is it ~10^{-40} sec?

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)
  - Sigl, Lee, Bhattacharjee, Yoshida PRD 59,043504 (1998)
  - Barbot, Drees, Halzen, Hooper, PLB 555, 22 (2003)
- 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: ~ $E^{-(1-1.5)}$
    - "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” Neutirnos



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**”)

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

$$\hookrightarrow \mu\nu$$

$$\hookrightarrow e\nu\nu$$

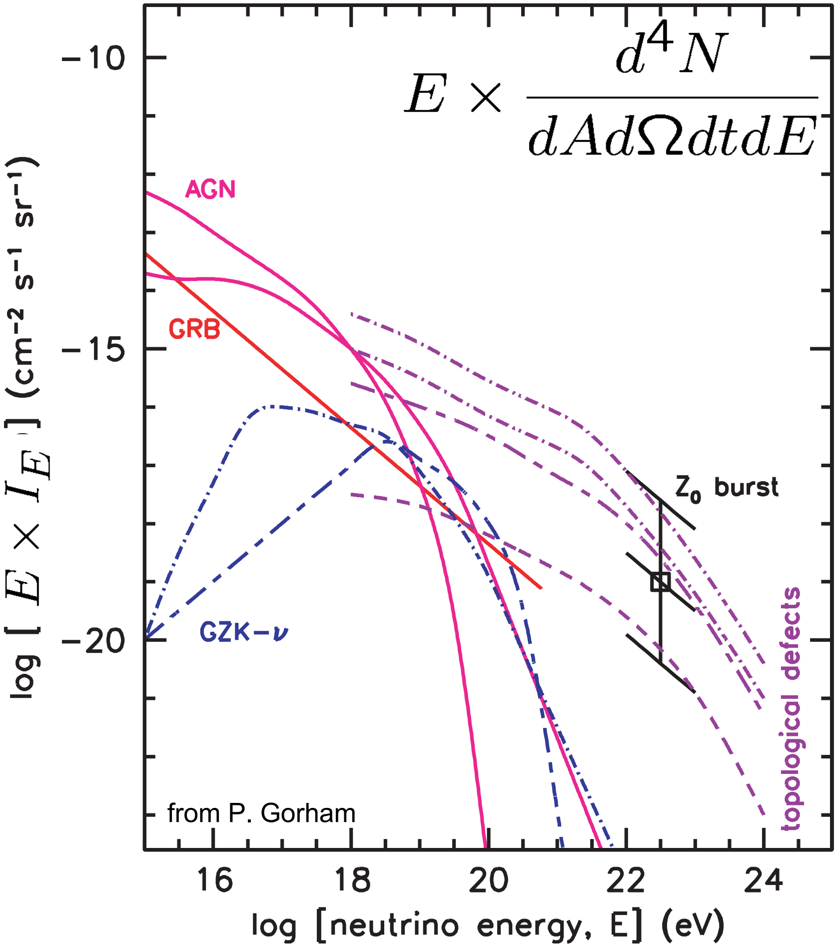
“guaranteed” neutrinos

Summary UHE ν Models

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

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

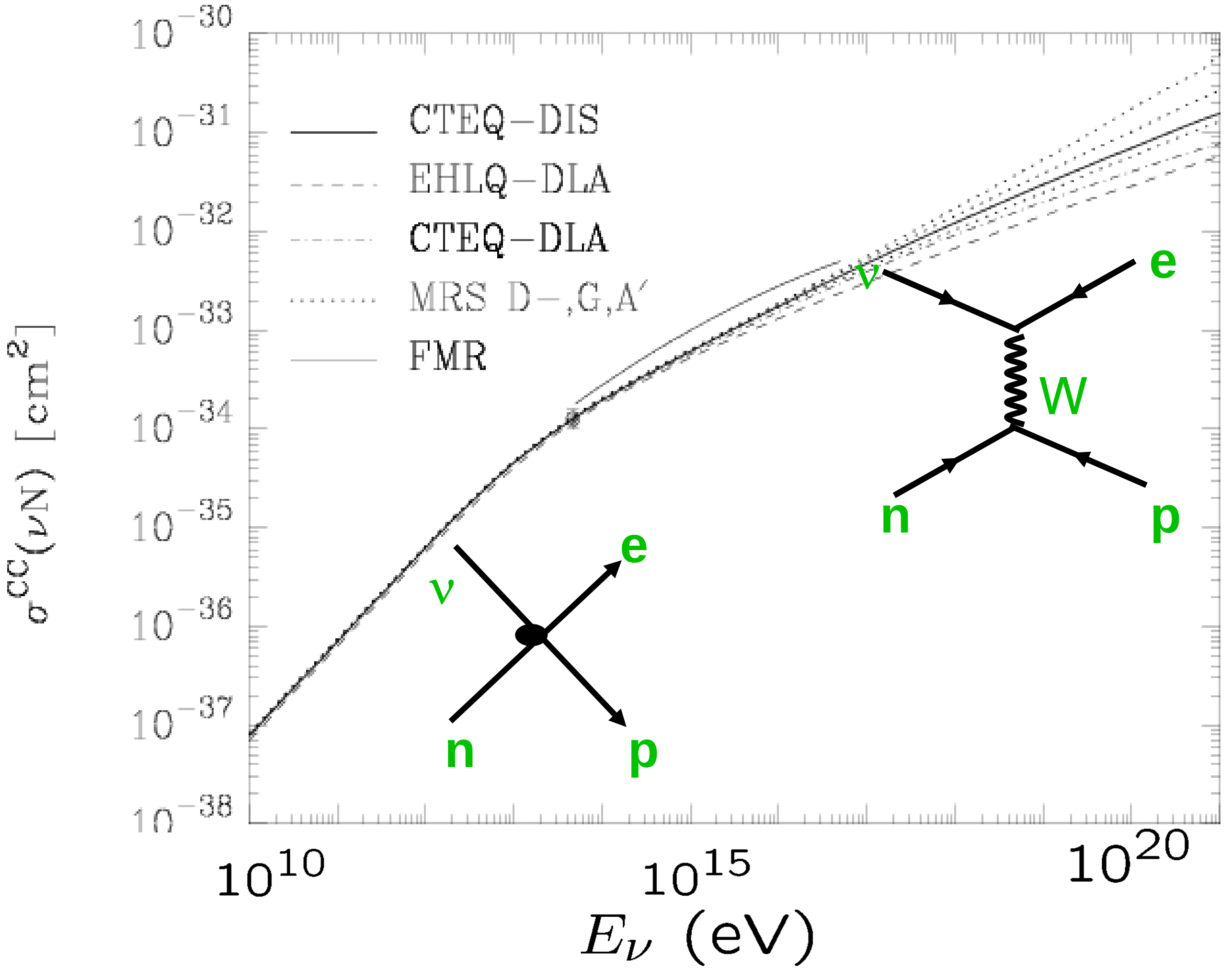
- Possible point of confusion:
  - Models give brightness
  - But, experiments measure intensity



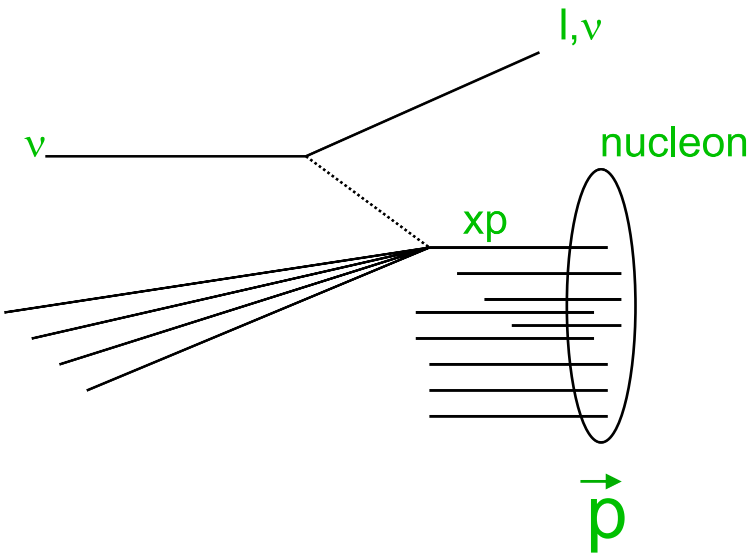
Neutrino interactions

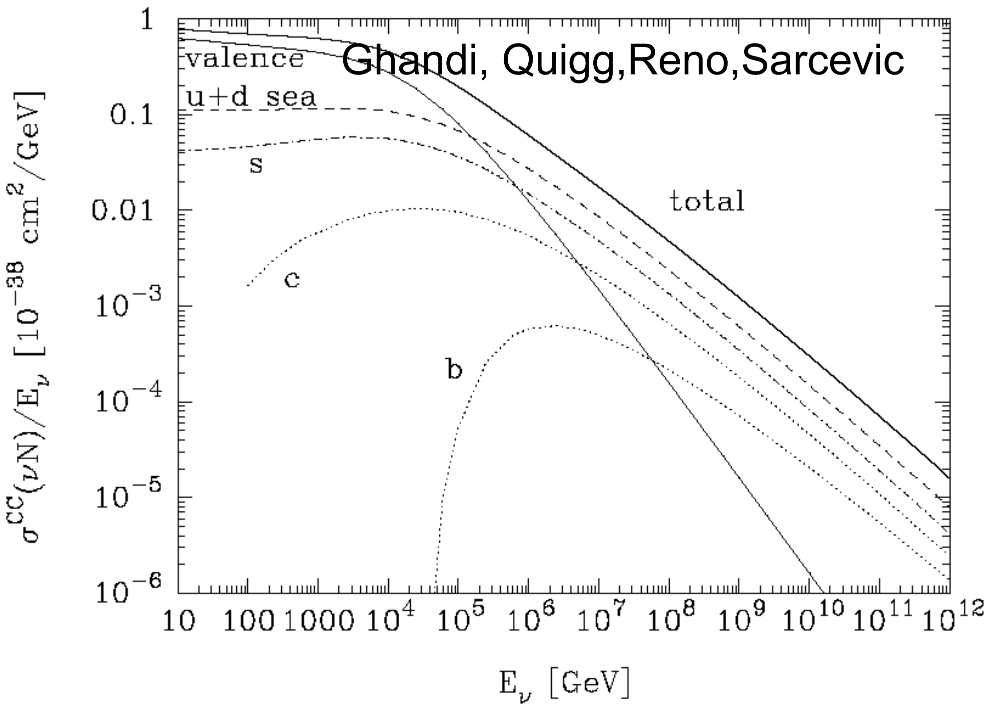
Most commonly used:

Ghandhi et al., Astropart. Phys. 5, 81 (1996):



B&B physics with ν cross section




Ghandi, Quigg,Reno,Sarcevic

- HERA tests proton structure to $x \sim 10^{-4}$ (only 10^{-2} at “high” Q^2)
- UHE ν 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
  - $E_{cm} = [2\, m_p\, E_\nu]^{1/2} \Rightarrow 150$ TeV for $E_\nu = 10^{19}$ eV
  - $\sigma_{SM}(\nu+N) \sim 10^{-7}$ £ $\sigma_{SM}(p+N)$
- Large extra dimension models could enhance ν cross section
  - Gravity could become strong at $E_{CM}=M_D$
  - Non-perturbative effects could produce KK-exitations, string excitation, pea-branes, micro-BH above E_{CM}

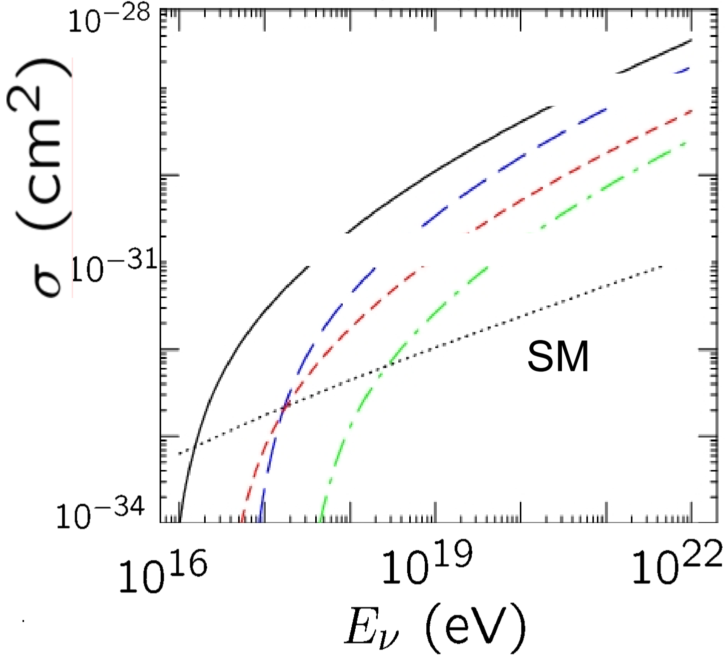
$$M_D = [\frac{M_{pl}^2}{8\pi r_c^n}]^{\frac{1}{2+n}} \text{ where } M_{pl} \equiv 10^{28}\text{eV}$$

- Astrophysics and laboratory limits still allow
  - $n=4$, $M_D > 10$ TeV
  - n¸ 5 $M_D>1$ TeV

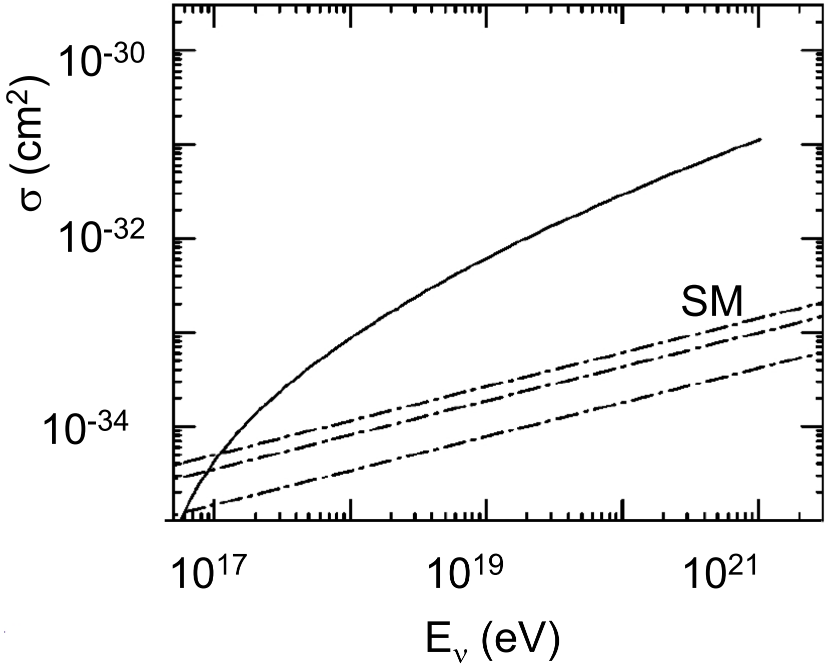
Enhancement of UHE Neutrino Cross Section

Sample predictions for M_D~1 TeV, n~6-7:

Alvarez-Muniz,Feng,Halzen,Han,Hooper
PRD65, 124015 (2002)



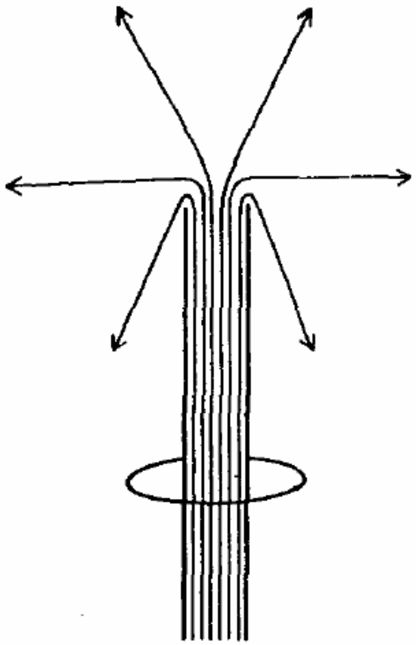
Anchordoqui,Feng,Goldberg,Shapere,
PRD65, 103002 (2002)



- ●Caveat: not all energy goes into BH or excitation, and need minimum energy for classical BH formation.
- ●UHE ν cross sections could be up to ~100£ 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 ~10^{14} eV.
  - E in extra-gal. magnetic fields ~ 10^{24} eV
- Parker bound (10^{-15} cm^{-2} s^{-1} sr^{-1})
  - c.f. UHECR>10^{20} eV (~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.



$$\exp(-ie \oint \mathbf{A} \cdot \mathbf{dr}) = 1$$

$$eg = \frac{n}{2}$$

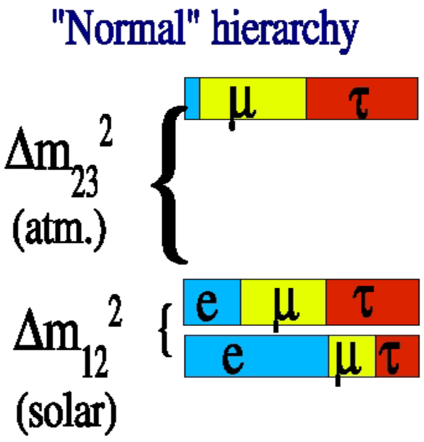
Neutrino Telescopes for Direct Monopole Detection

Wick, Kephart, Weiler, Biermann

- Relativistic monopoles mimic particle with large charge: at least Z~68
  - produce EM showers along path by pair-production, photo-nuclear
  - continuously produces shower along its path → unique signature
- WKW estimate $F<10^{-18}$ cm^{-2} s^{-1} sr^{-1} for a km^3 detector for 1 year.
  - SalSA could do ~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

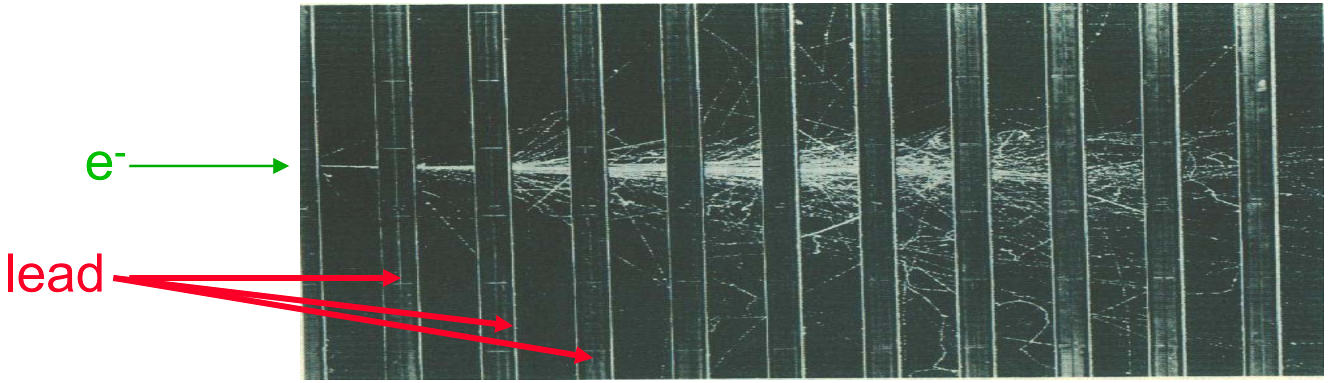
- Critical parameter for neutrino oscillations and decay is proper time, L/E.
  - Solar neutrinos: 150,000 km/5£10^6 eV = 30 m/eV
  - “SalSA” neutrinos from 4 Gpc/10^{17} eV = 10^9 m/eV
- No SM ν decay from SM on these time scales
  - However, ν ! ν + J   (J= Majoran)
  - Flavor ratios would be from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



- Beacom,Bell, Hooper, Pakvasa, Weiler
  - $\nu_e : \nu_\mu : \nu_\tau$
  - ~1:1:1 !   5:1:1

Beyond km^3 ?
Two 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: $e^+ + e^-_{\text{(at rest)}} \rightarrow \gamma + \gamma$

Two Good Ideas by Gurgen Askaryan (I)

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

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

Each charge emits field $|E| \propto e^{ik\cdot r}$

and Power $\propto |E_{tot}|^2$

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

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

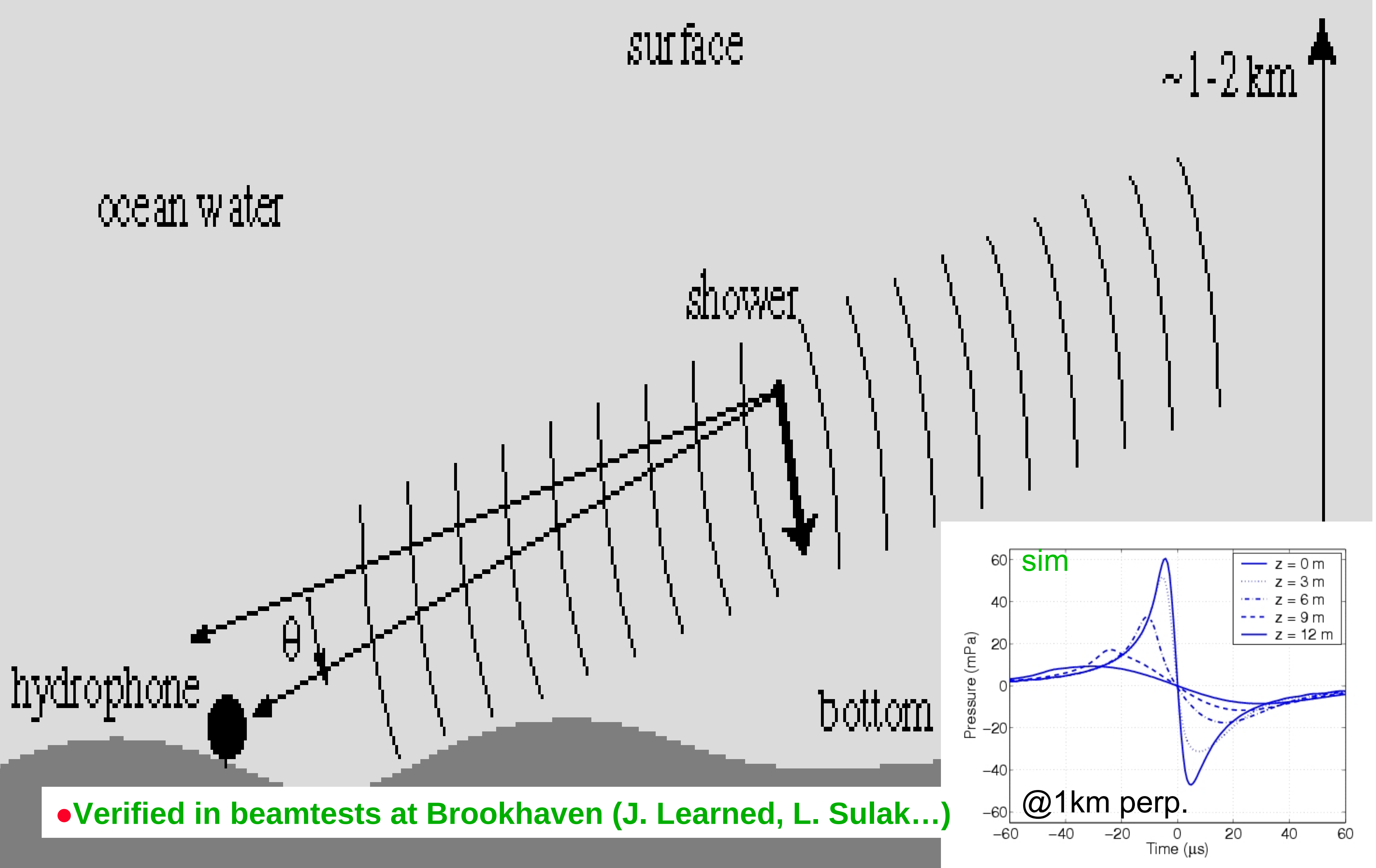
$\lambda \gg R_{Moliere}$ (microwaves), coherent $\Rightarrow$ **$P \propto N^2$**

Confirmed with Modern simulations + Maxwell’s equations:

(Halzen, Zas, Stanev, Alvarez-Muniz, Seckel, Razzaque, Buniy, Ralston, McKay …)

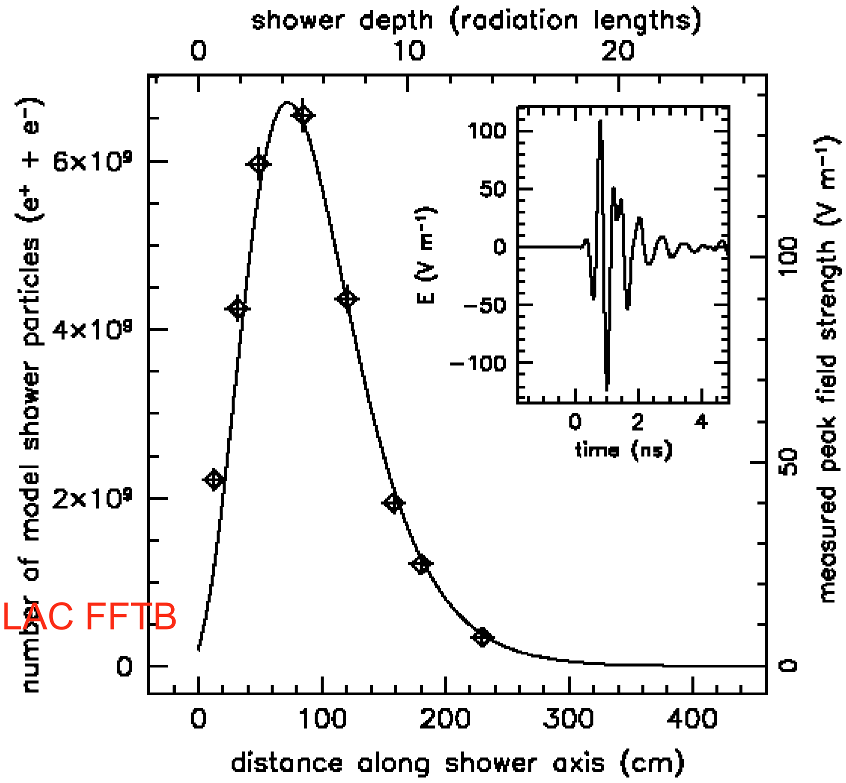
Another Good Idea from Askaryan (II): Acoustic Detection

(1957)

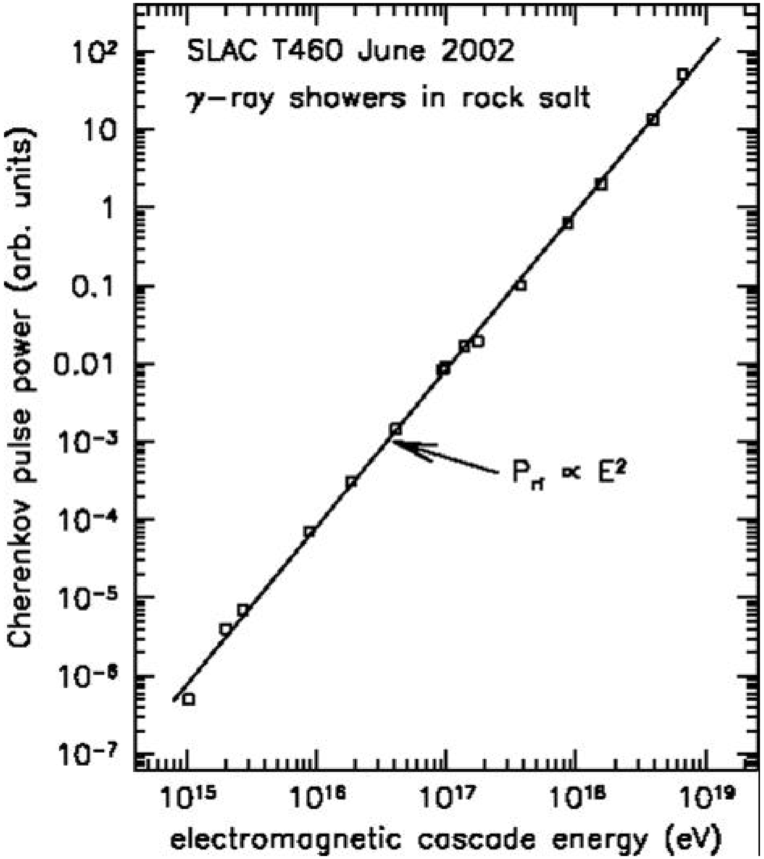


- **Verified in beamtests at Brookhaven (J. Learned, L. Sulak…)**

The SLAC Salt and Sand boxes



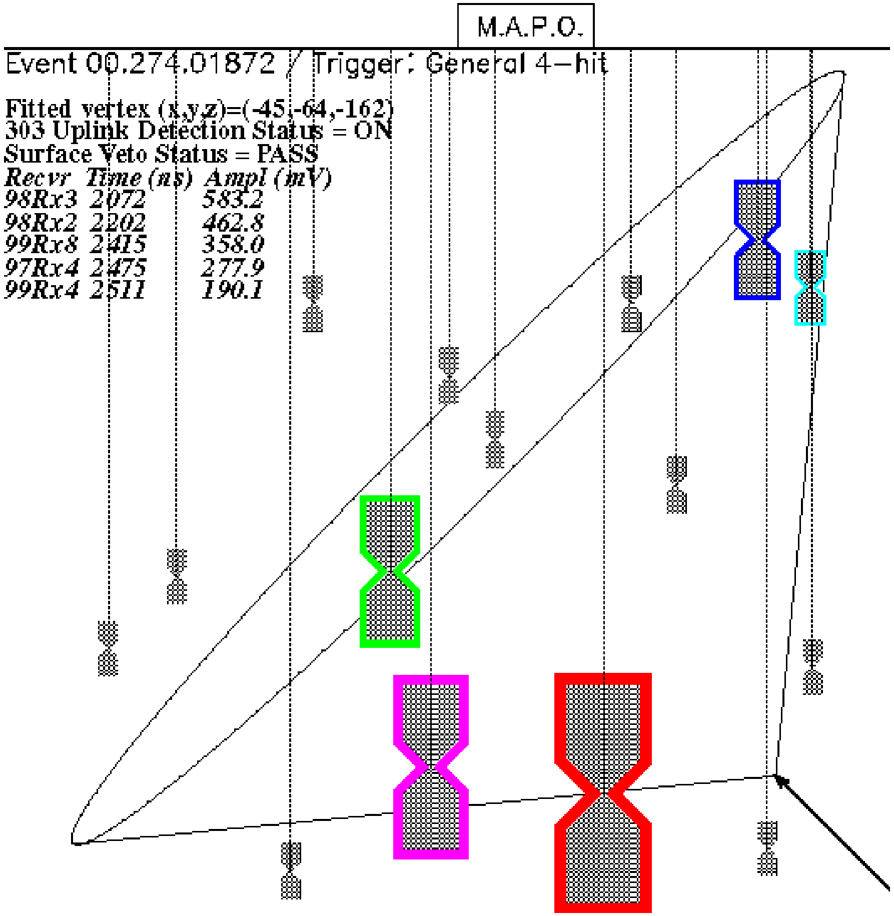
SLAC FFTB



- Amplitude expected
- 100% linearly polarized
- Cherenkov angle

RICE Experiment

- “Radio in Ice Experiment”
- Dipoles (100-1000 MHz) on AMANDA strin @ South Pole
- 200 x 200 x 200 meter array
- Uses long attenuation length (view to ~ 7k
- E_ν>~10^{17} eV
- [VΔΩ]» 10 km^3-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



Event 00.274.01872 / Trigger: General 4–hit

Fitted vertex (x,y,z)=(-45,-64,-162)
303 Uplink Detection Status = ON
Surface Veto Status = PASS

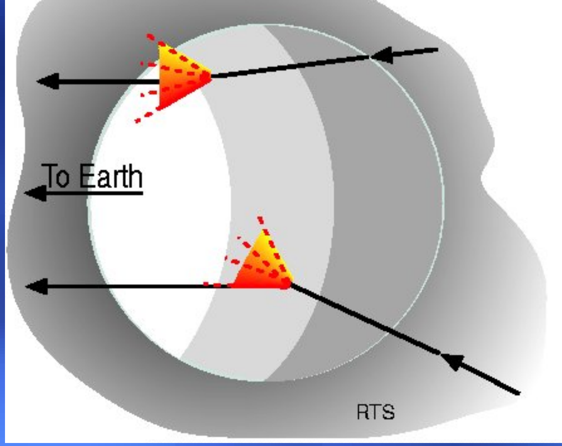
Recvr	*Time (ns)*	*Ampl (mV)*
98Rx3	*2072*	*583.2*
98Rx2	*2202*	*462.8*
99Rx8	*2415*	*358.0*
97Rx4	*2475*	*277.9*
99Rx4	*2511*	*190.1*

Candidate event

I. Kravchenko, *et al*., ICRC-03, astro-ph/0306408

Goldstone Lunar UHE Neutrino Search (GLUE)

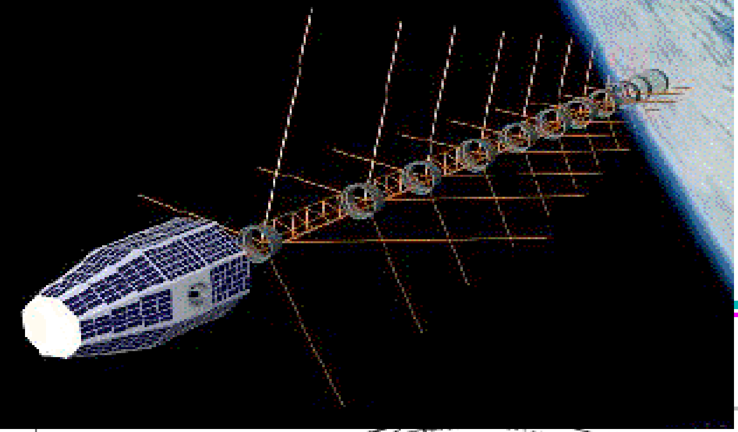
P. Gorham *et al.*, PRL 93, 041101 (2004)



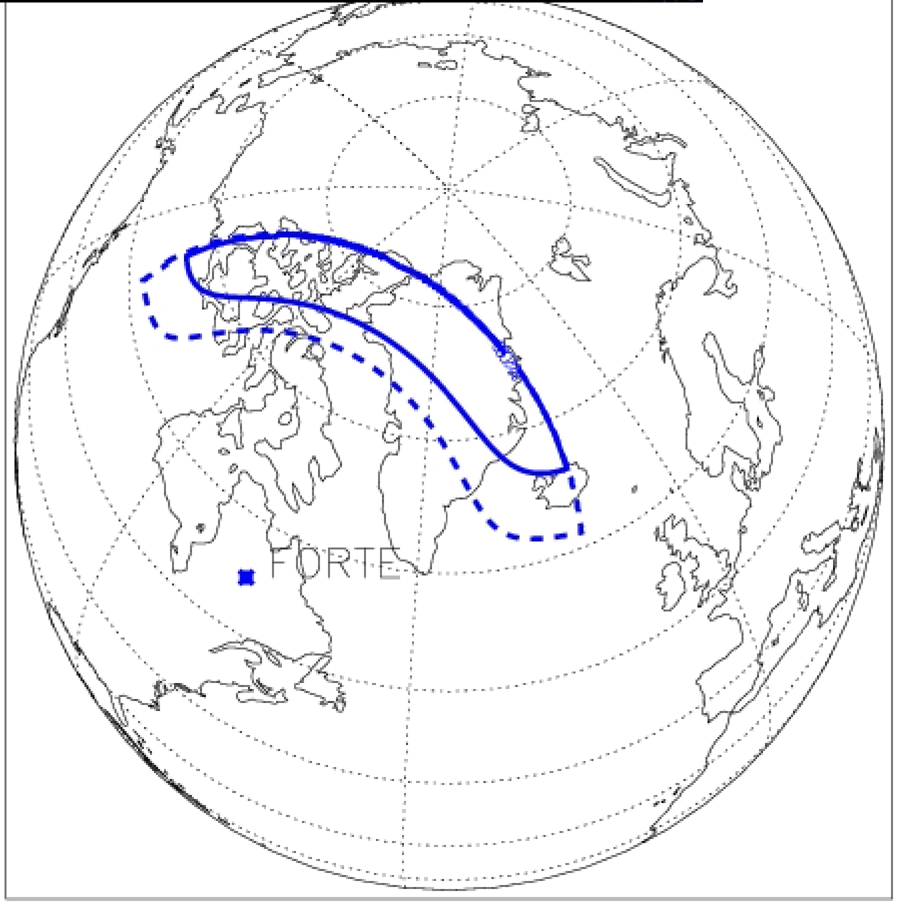
Two antennas at JPL's Goldstone, Calif. Tracking Station

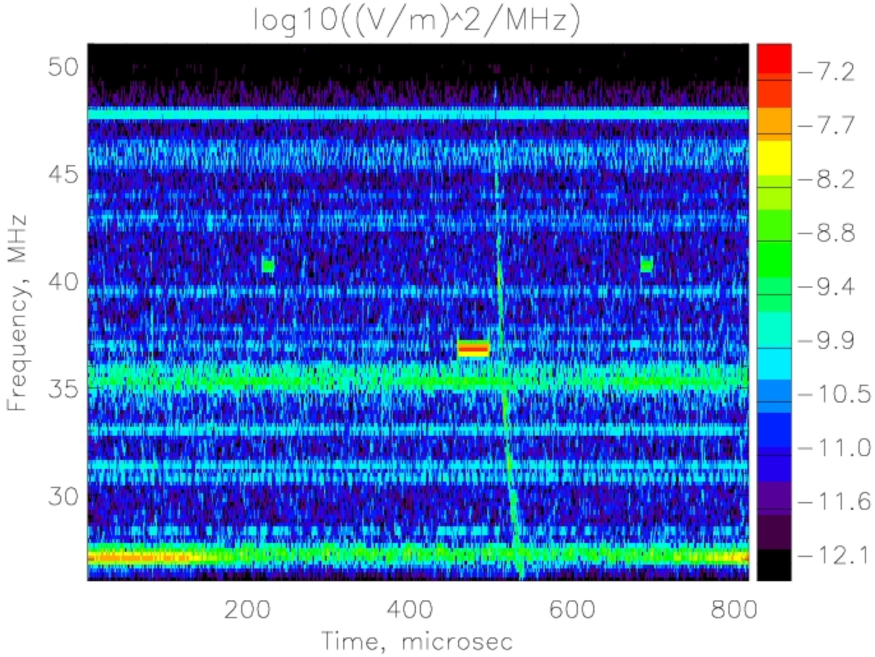
- limits on $>10^{20}$ eV ν's
- regolith atten. len. ~20 m
- ~123 hours livetime
- $[V\Delta\Omega]_{eff}$~600 km^3-sr
- datataking complete

Earlier experiment: 12 hrs using single Parkes 64m dish in Australia: T. Hankins *et al.*, MNRAS 283, 1027 (1996)



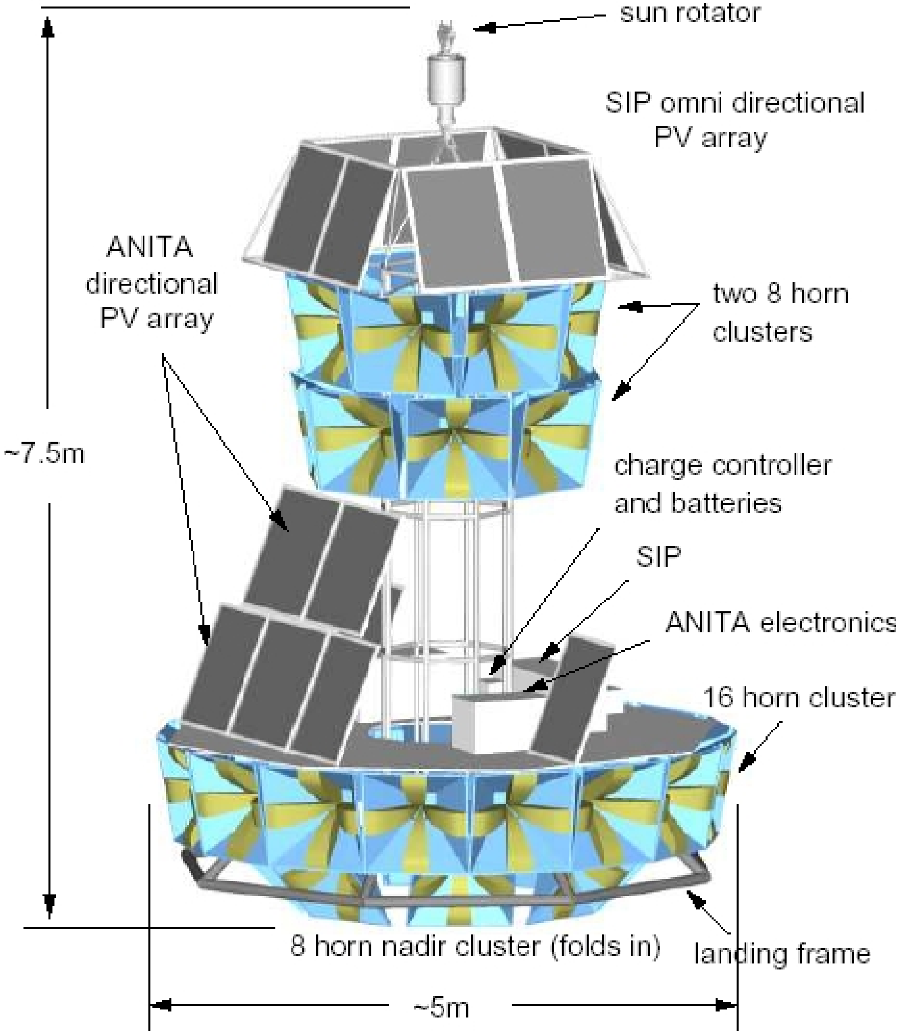
Example Forte Event

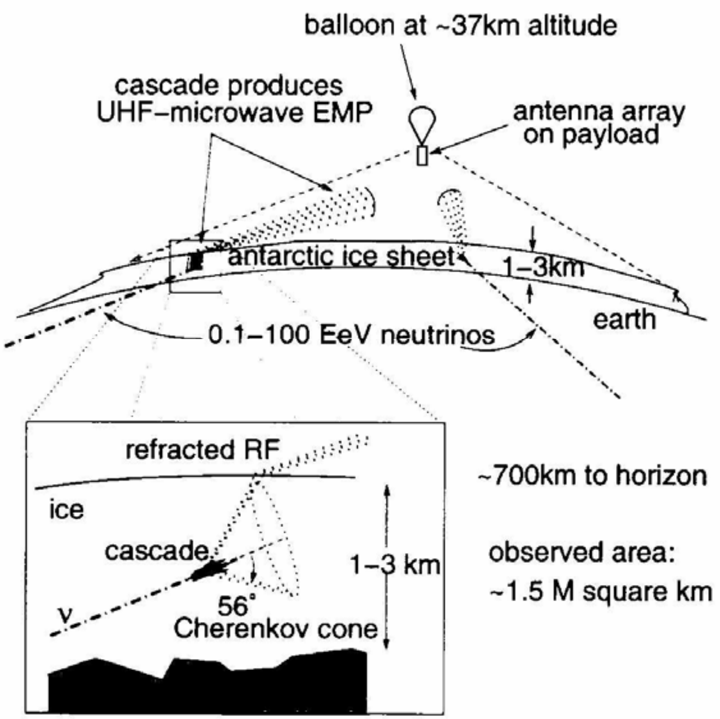




- E_{ν}^{thresh} » 10^{22} eV
- $[V\Delta\Omega]$ ~ 100,000 km^3 sr, but threshold extremely high.

ANITA





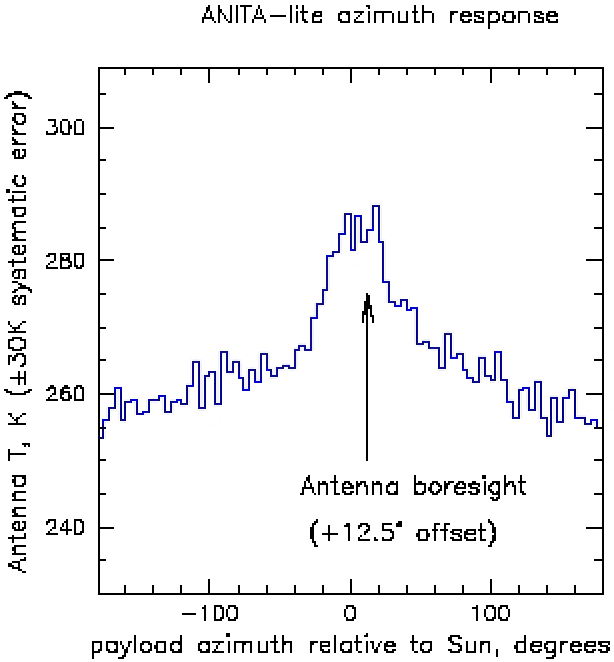
First flight in 2006-07

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

$[V\Delta\Omega]$~20,000 km^3-sr

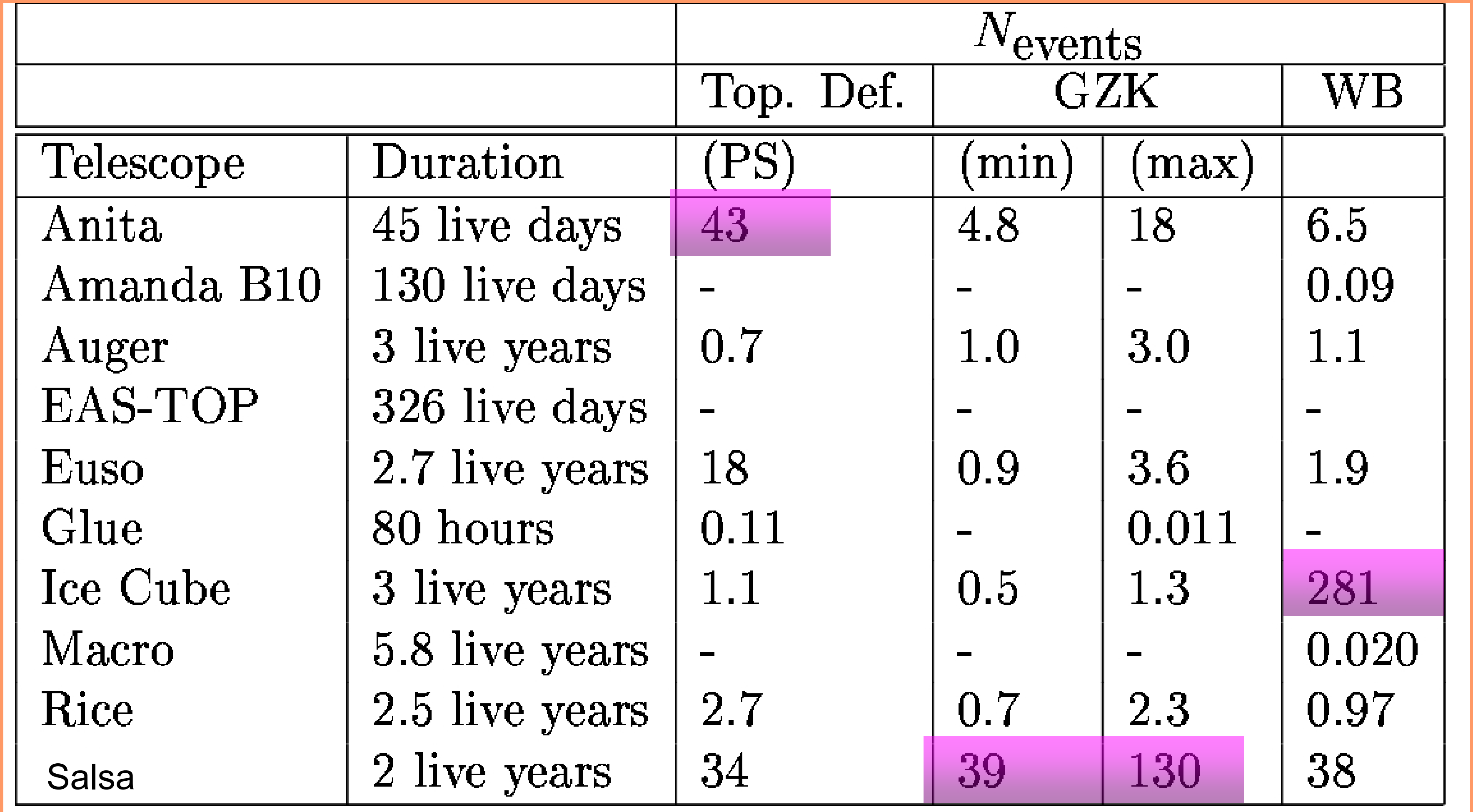
P. Gorham, et al., NASA concept study report (2004)

Anita-LITE



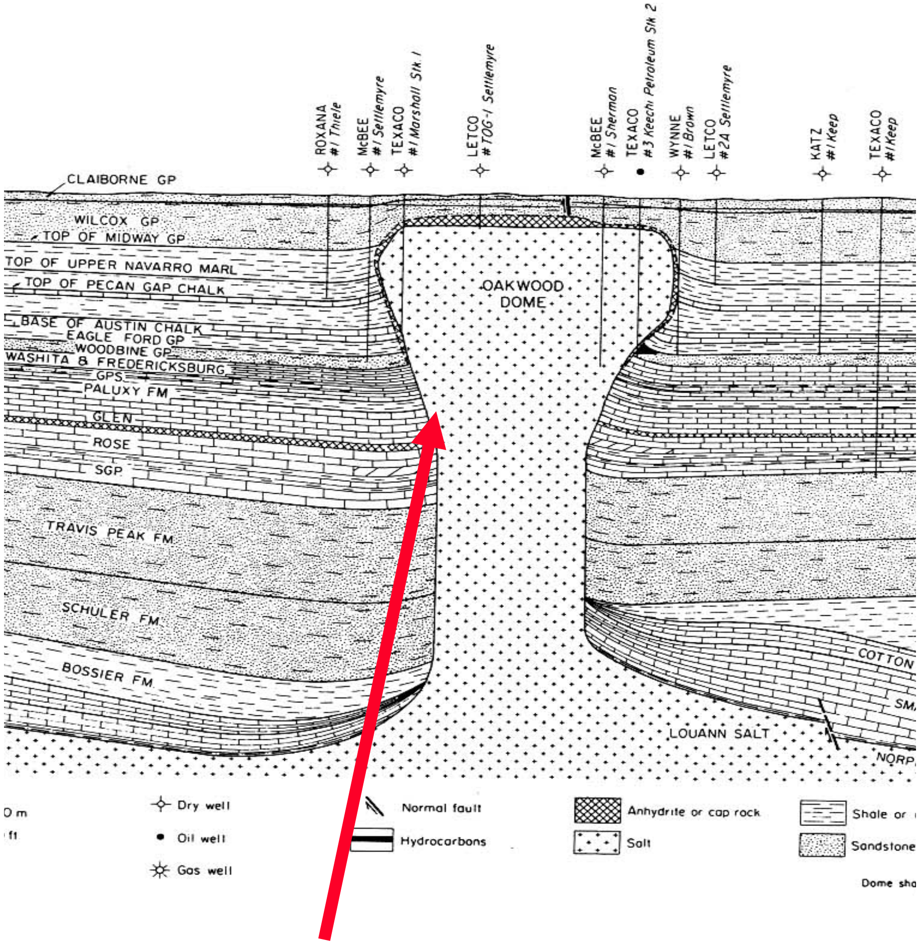
- 18 day flight in 2003-04
- Antarctica proved very radio quiet
- Observed the Sun as calibration
- Ground pulses observed w/120 psec timing – gives $\delta\phi=2^{\pm}$, $\delta\theta = 0.5^{\pm}$

Comparing using Models



		N_{events}			
		Top. Def.	GZK		WB
Telescope	Duration	(PS)	(min)	(max)	
Anita	45 live days	43	4.8	18	6.5
Amanda B10	130 live days	-	-	-	0.09
Auger	3 live years	0.7	1.0	3.0	1.1
EAS-TOP	326 live days	-	-	-	-
Euso	2.7 live years	18	0.9	3.6	1.9
Glue	80 hours	0.11	-	0.011	-
Ice Cube	3 live years	1.1	0.5	1.3	281
Macro	5.8 live years	-	-	-	0.020
Rice	2.5 live years	2.7	0.7	2.3	0.97
Salsa	2 live years	34	39	130	38

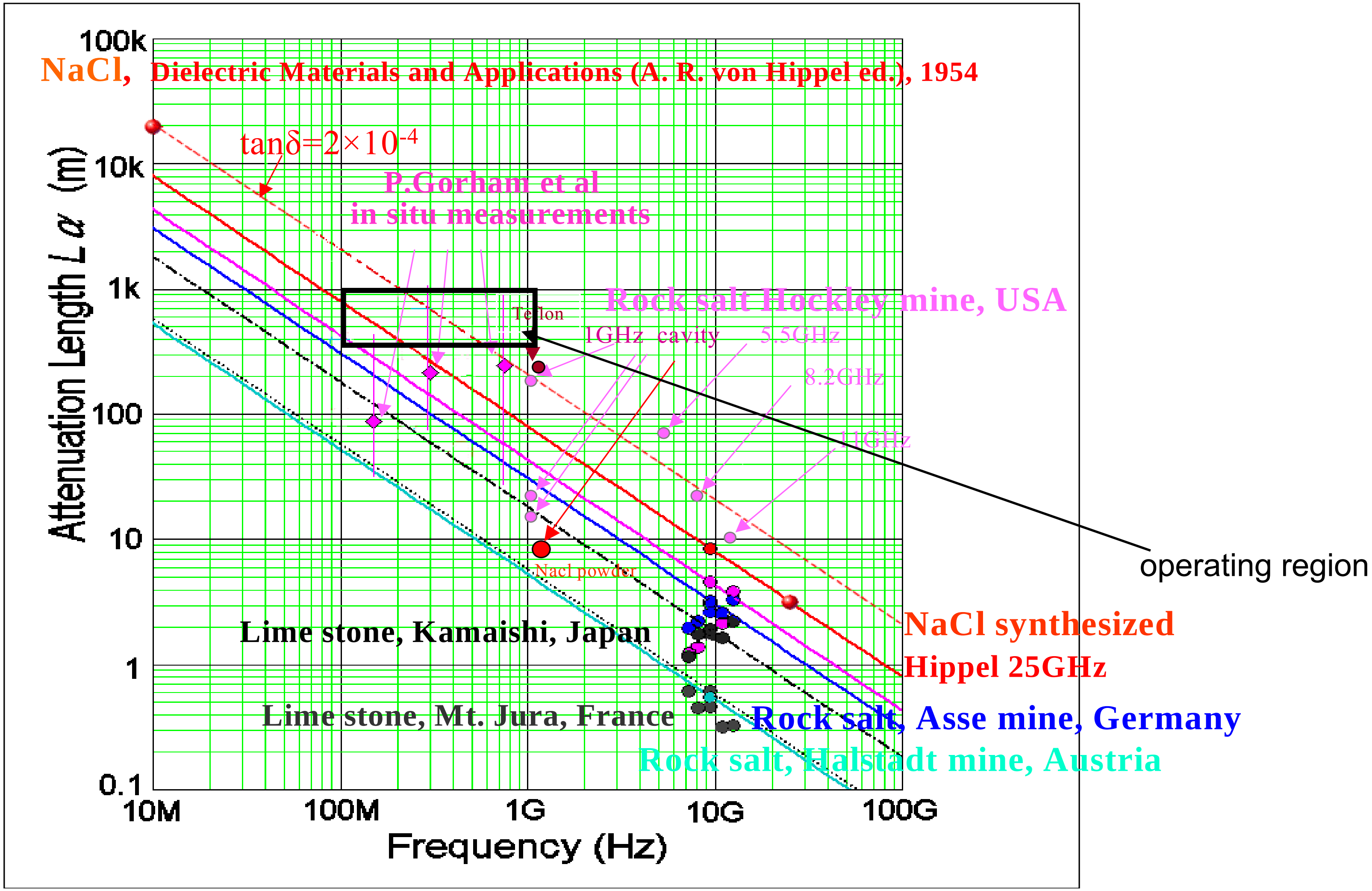
SalSA:
A Next Generation UHE neutrino dtector



diapir action pushes out water

- ~25km^3 in upper 3km of dome (75 km^3 water-equiv.)
  - >2£ 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 atten. 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

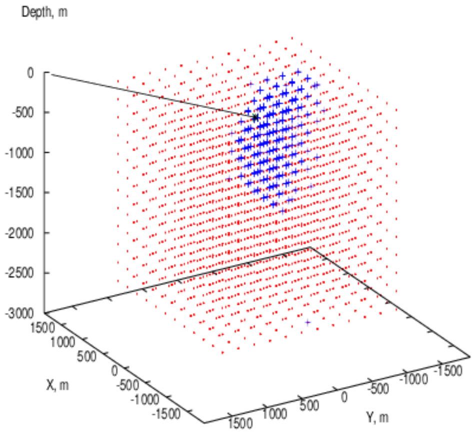
Salt Attenuation



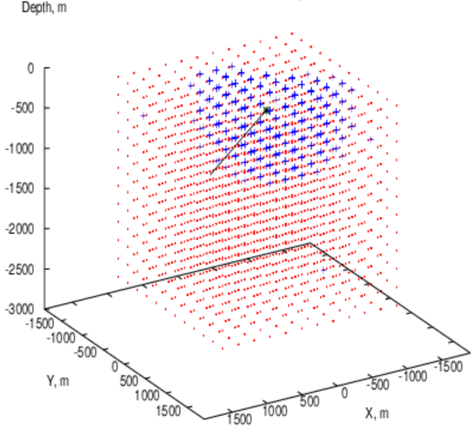
- Need to confirm with more sensitive attenuation length measurements
- Measurents so far, consistent with 300K thermal noise

Simulated Events

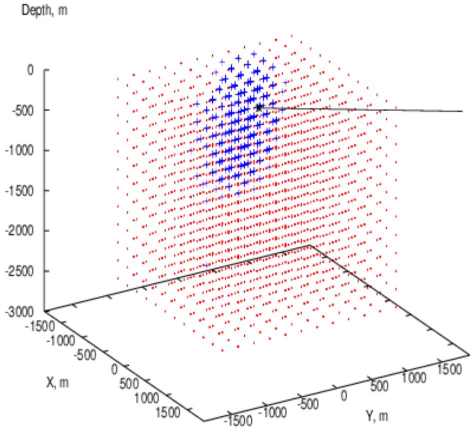
Shower energy = 10^{19} eV   neutrino direction: alt= 8 °, az=134°



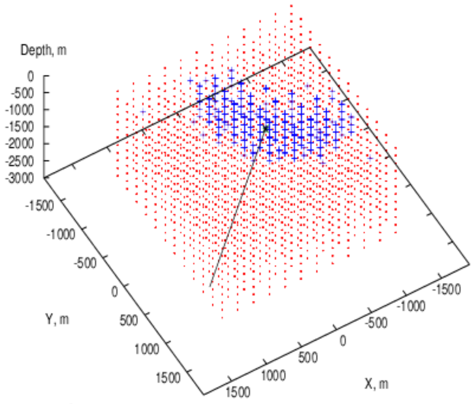
alt=28°, az=239°



alt=28°, az=149°

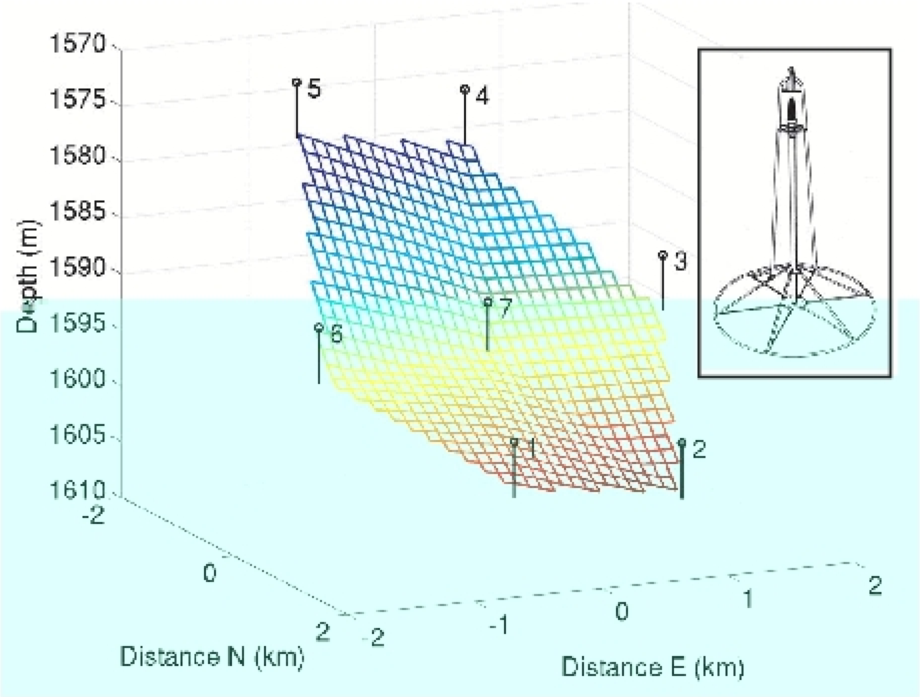


alt=28°, az= 59 °



alt=68°, az=149°

Acoustic Detection



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

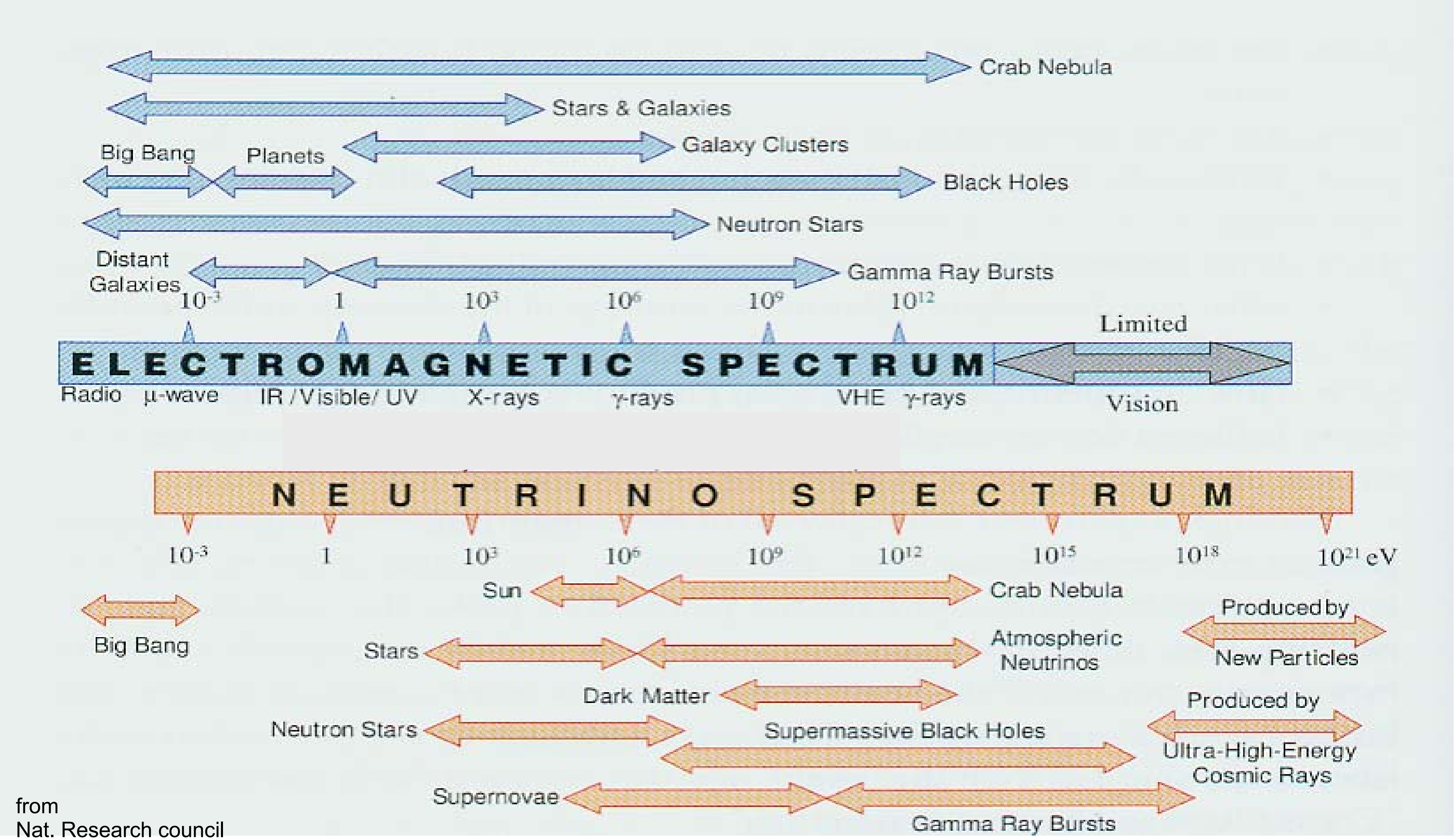
Roadmap for the Next Generation Salt Detector

- 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 ν 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 β ~ 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

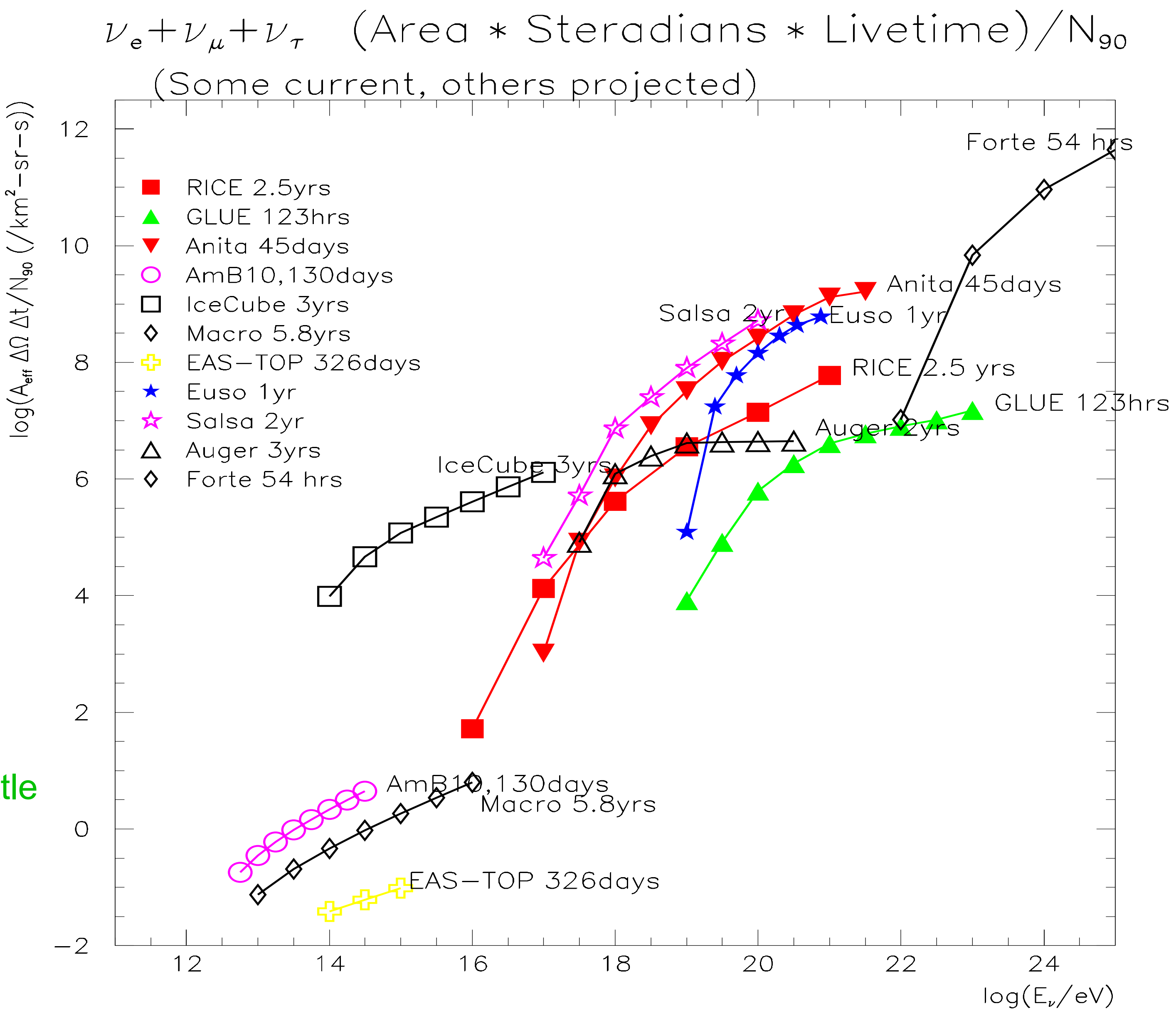
• Conclusion-II   (for an astronomer):



from
Nat. Research council

Backup Slides

Comparison of Detector Discovery Potential: $[A\Delta\Omega]$ £ Δt_{live}



- 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 ΔΩ] Δt vs. energy (& background) for each neutrino flavor describes experiment
  - $$N_{obs} = \int I_E \times [A\Delta\Omega]\; dA\,d\Omega\,dE\,dt$$
  - For example: [A ΔΩ] for a flat,black paddle=A£2π
  - [V ΔΩ]=[A ΔΩ]£ L_{int} accounting for neutrino cross section vs. energy
  - (Discovery potential also depends on background)

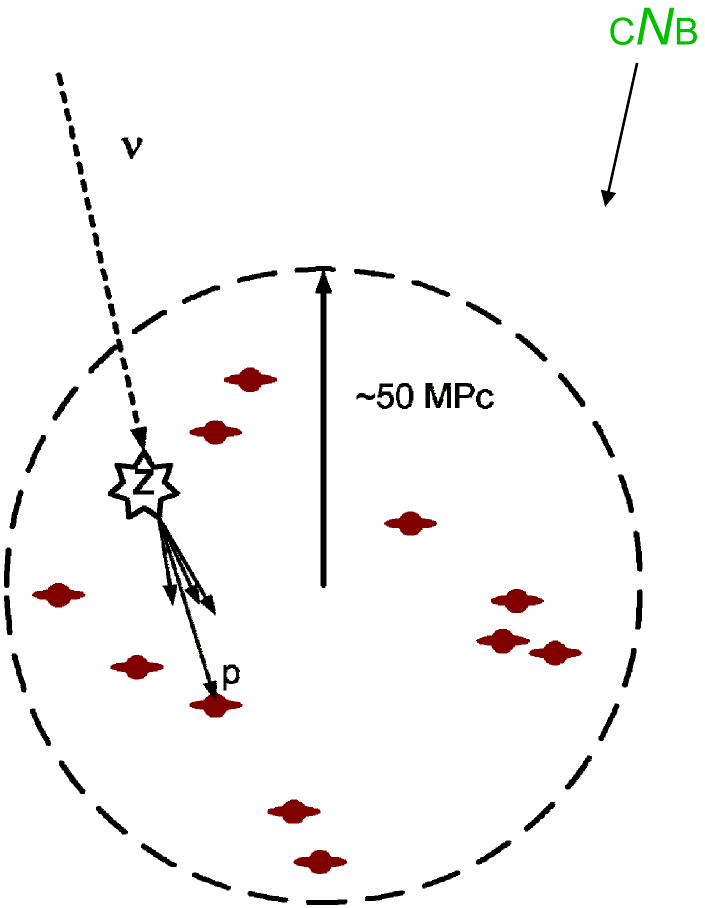
- Need many km^3 of material to detect > 10^{15} eV

- Here I'll give (my estimates of):
  - E_ν^{thresh} (approx.)
  - typical [V ΔΩ] and Δt
  - Compare <u>at the end</u> with [A ΔΩ] Δt for detection

Z-bursts?

If local enhancement of local CNB:

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



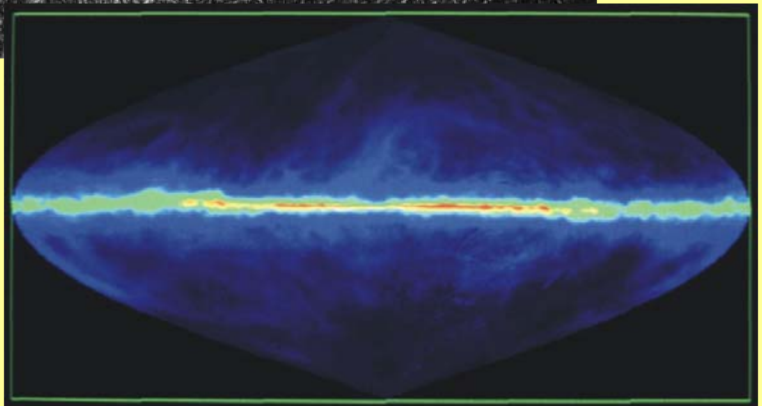
if $m_{\nu}^{CNB} \sim 0.05 - 0.5$ eV

⇒ $E_{\nu} \sim 10^{22-23}$ eV

⇒ Would be a minimum flux of 10^{23} eV neutrinos

Astrophysics Motivations:
The range of photon astronomy

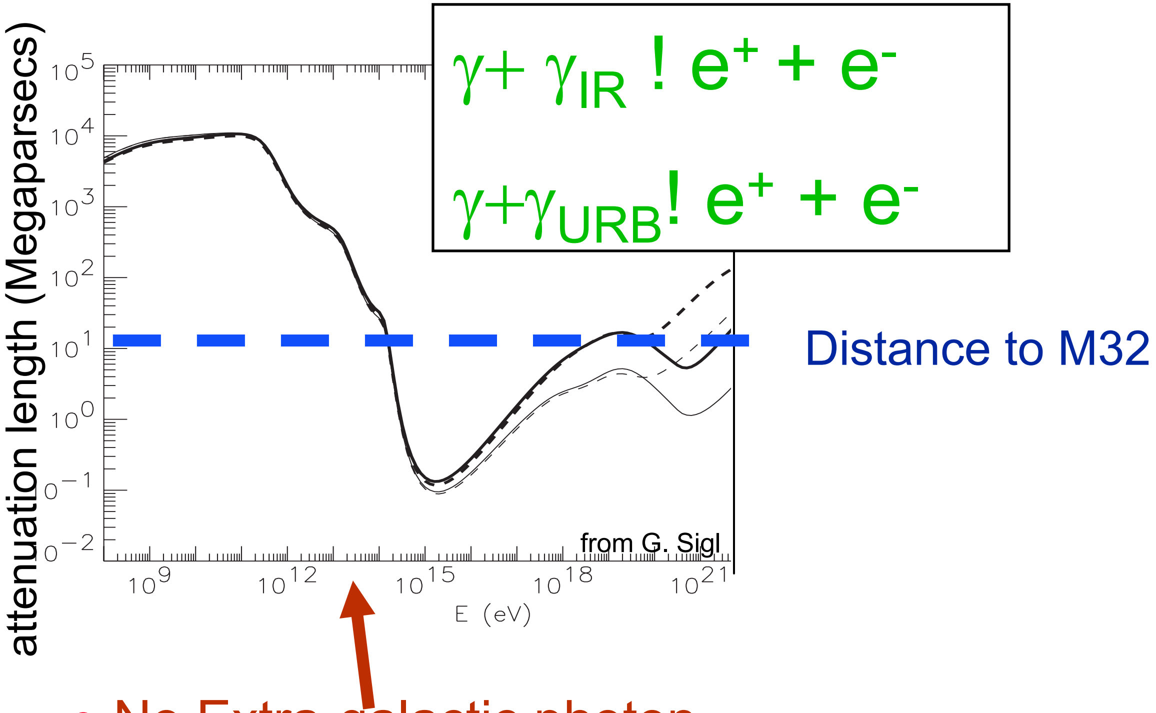
Radio Astronomy
$<10^{-7}$ eV photons



Atmospheric Cherenkov
$>10^{12}$ eV photons

…and everything in between

The end
of photon astronomy



$\gamma + \gamma_{IR} \rightarrow e^+ + e^-$

$\gamma + \gamma_{URB} \rightarrow e^+ + e^-$

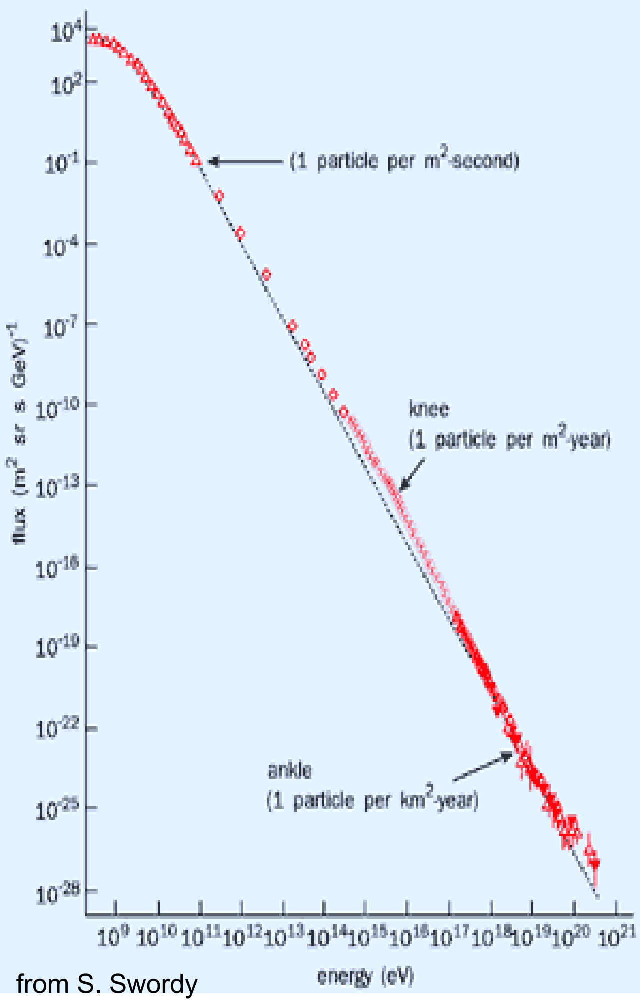
Distance to M32

from G. Sigl

- No Extra-galactic photon astronomy beyond ~10^{14} eV

No cutoffs for neutrinos

Beyond 10^{14} eV?



from S. Swordy

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

Sources are still a mystery:

AGN, GRBs?

- could produce ~1/E^2 neutrino flux

Neutrinos would point back:

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

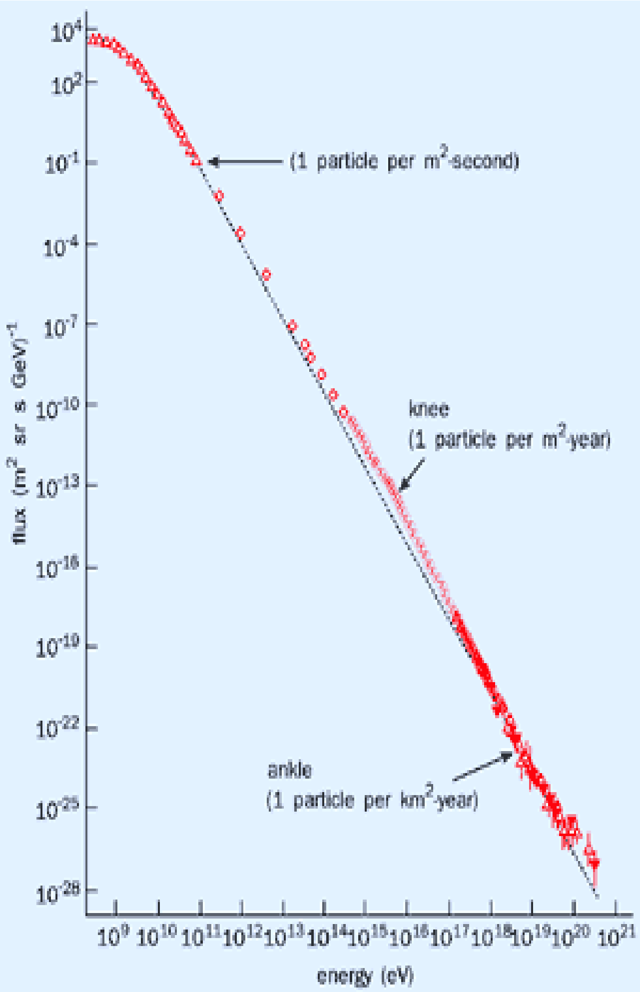
$$p + \gamma_{2.7K} \rightarrow \Delta^* \rightarrow n + \pi^{\pm}$$

$$\hookrightarrow \mu\nu$$

$$\hookrightarrow e\nu\nu$$

"guaranteed" neutrinos

How to instrument more than a few km^3 –sr?



Astrophysical processes are producing particles over at least <u>7 more</u> orders of magnitude

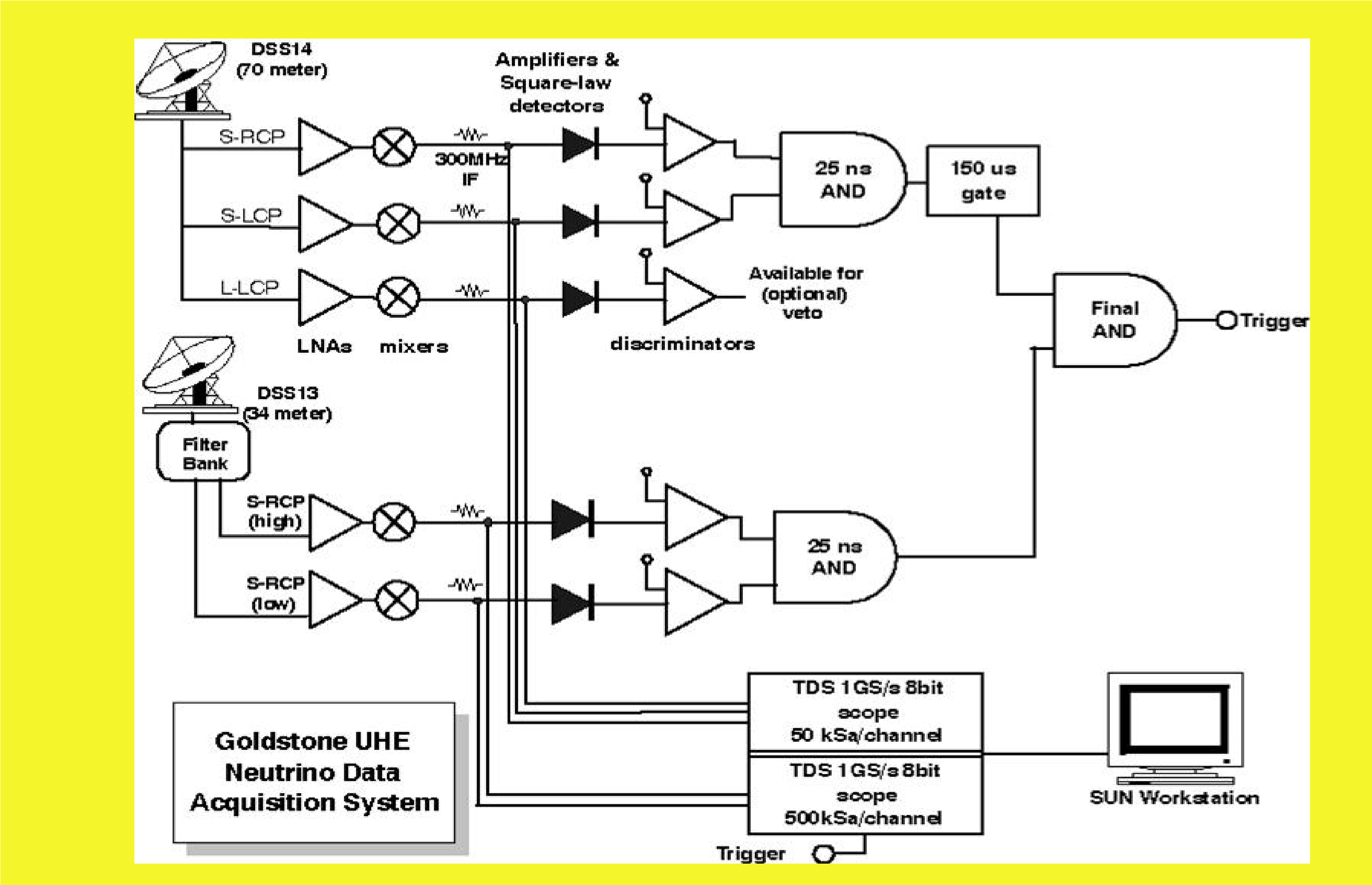
Neutrinos would point back:

- Sources may produce neutrinos directly
- or indirectly (“**<u>GZK process</u>**”)

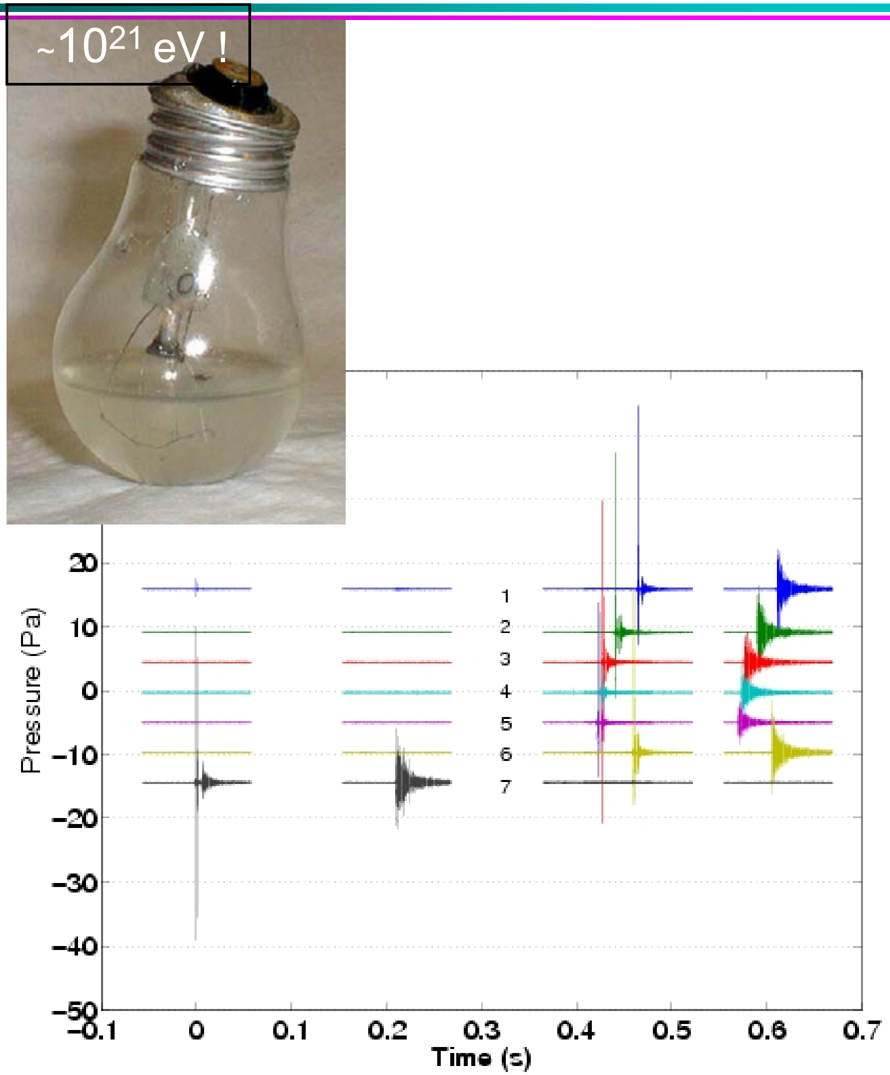
$$
\begin{aligned}
&p + \gamma_{2.7K} \rightarrow \Delta^* \rightarrow n + \pi^{\pm} \\
&\qquad\qquad\qquad\qquad\qquad\quad \hookrightarrow \mu\nu \\
&\qquad\qquad\qquad\qquad\qquad\qquad \hookrightarrow e\nu\nu
\end{aligned}
$$

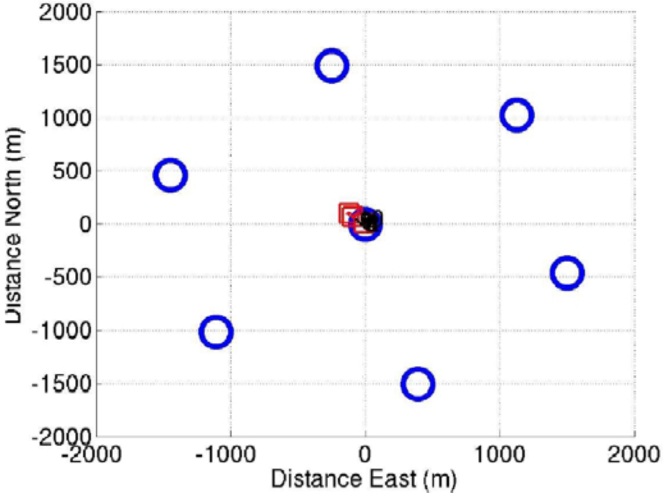
“guaranteed” neutrinos

A more detailed view of GLUE
(since common to most radio detection)



SAUND Calibration





- 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

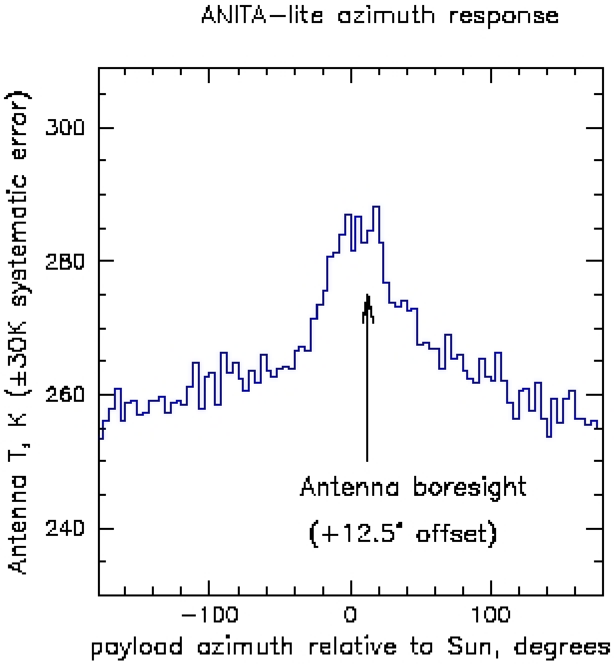
Stay Tuned…

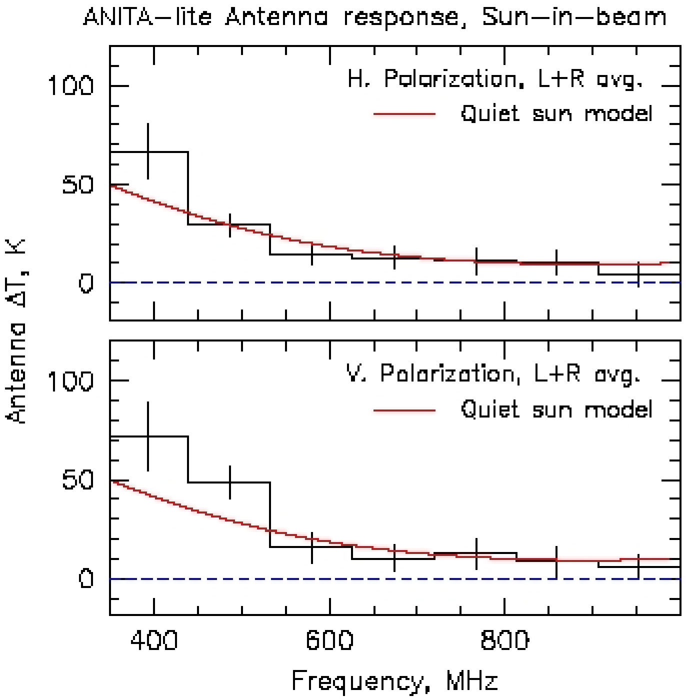
Other Acoustic Efforts (Acoustic workshop Sept ’03)

- 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 http://hep.stanford.edu/neutrino/SAUND/workshop/slides/index.html

Anita Lite
Signal and Noise



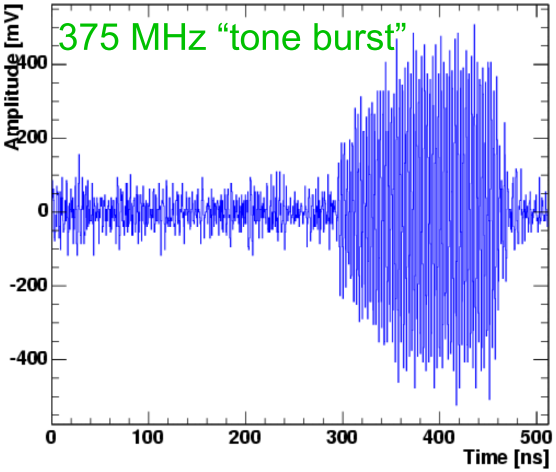


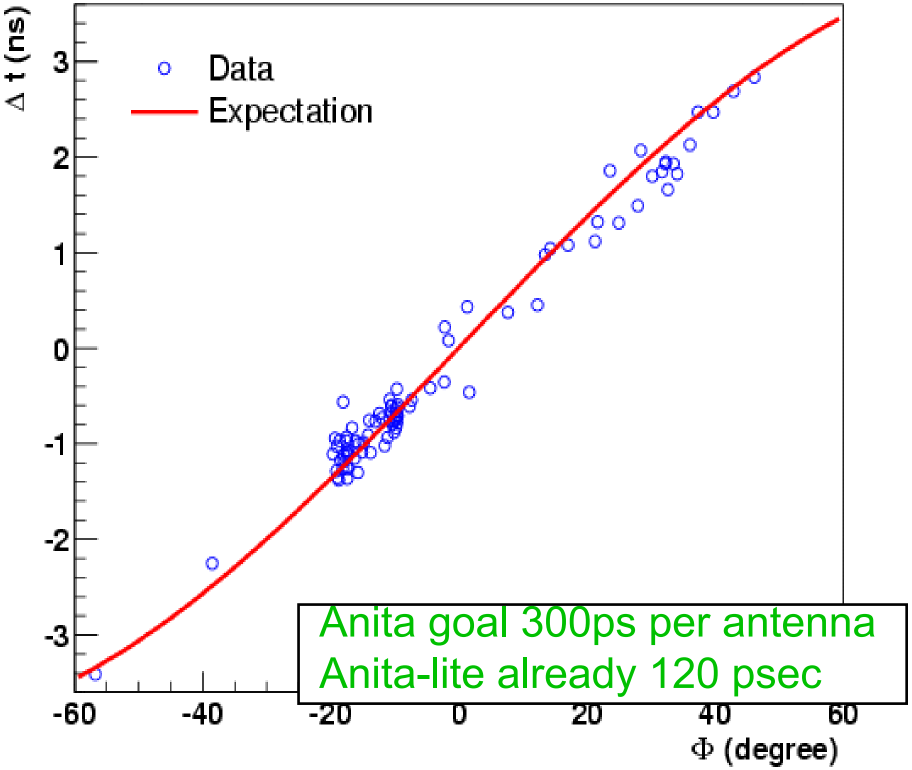
- Some on-board impulsive noise, will be removed for dedicated ANITA flight
- No evidence for off-payload impulsive noise beyond McMurdo Station horizon

Anita Lite Resolutions

Ground-to-payload pulse at ~250km

from Williams' Field





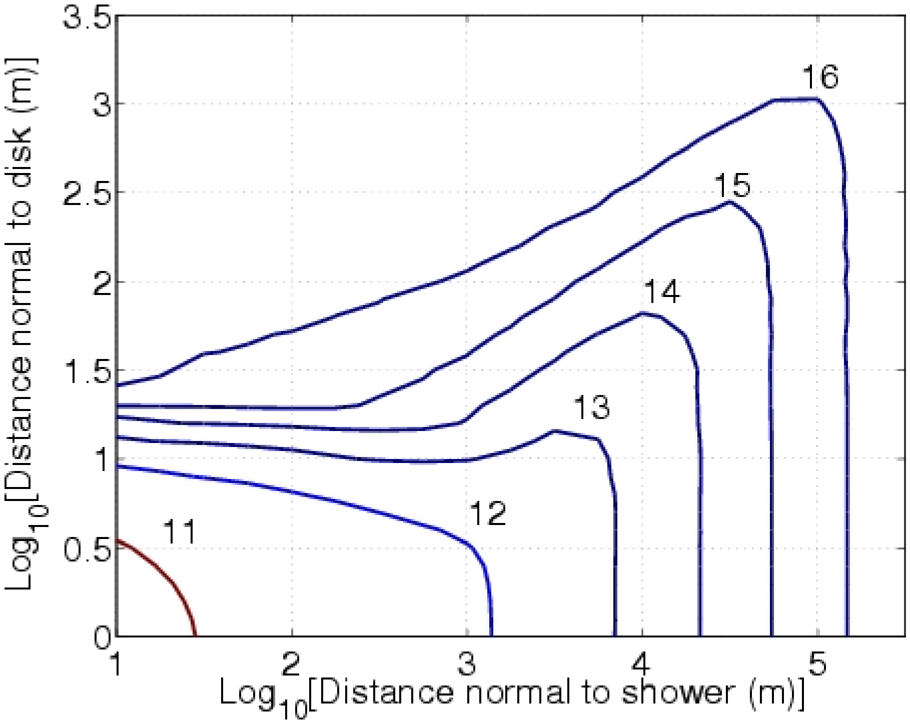
Anita goal 300ps per antenna
Anita-lite already 120 psec

- Anita resolution on RF direction

  δ θ » 0.5±

  δ φ » 2±

SAUND
Neutrino Search

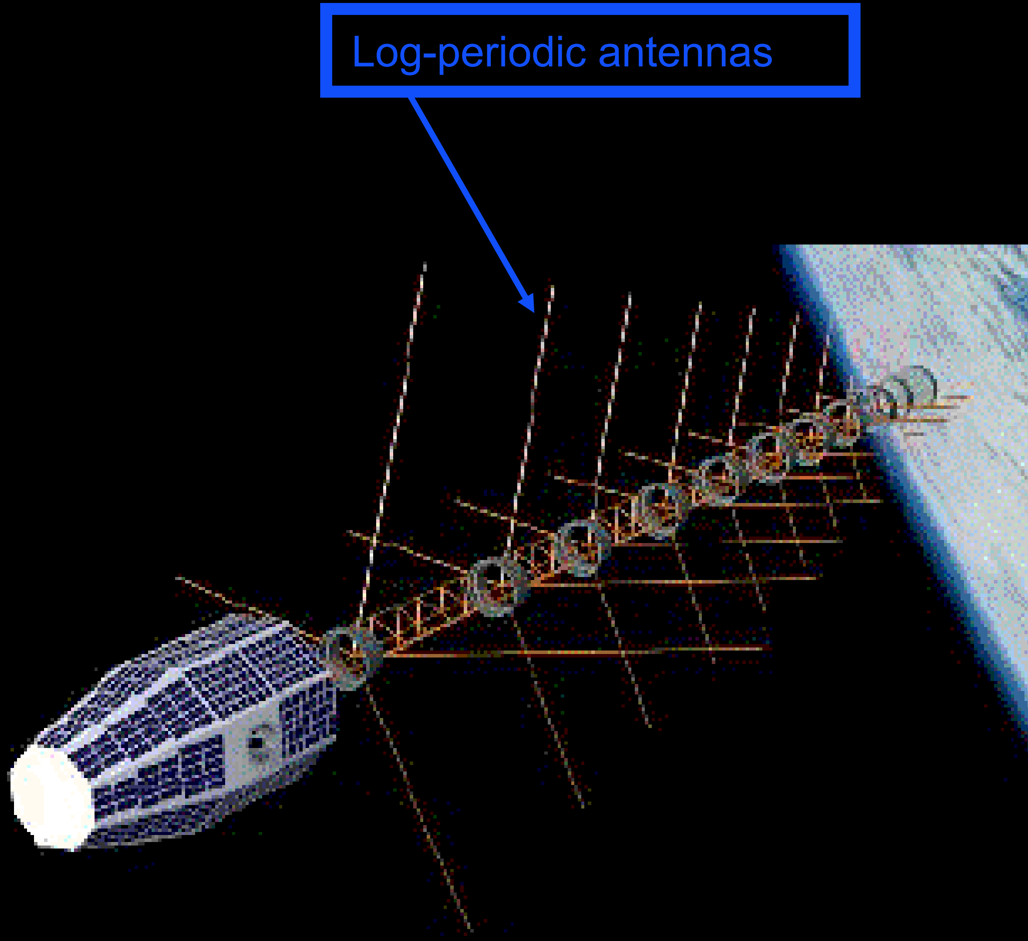


- $E_\nu \sim 10^{22}$ eV
- [V $\Delta\Omega$]~100 km^3-sr
- Not enough…

  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 km^3
  - 38 days £ 6%
- Can self-trigger on transient events 22MHz band in VHF band (from 30 300 MHz)
- Event characterization
  - polarization
  - ionospheric group delay and birefringence
  - timing



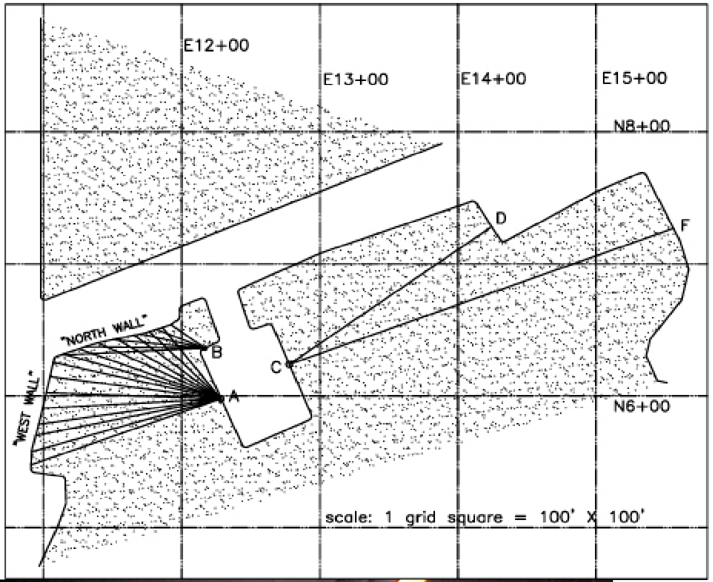
Log-periodic antennas

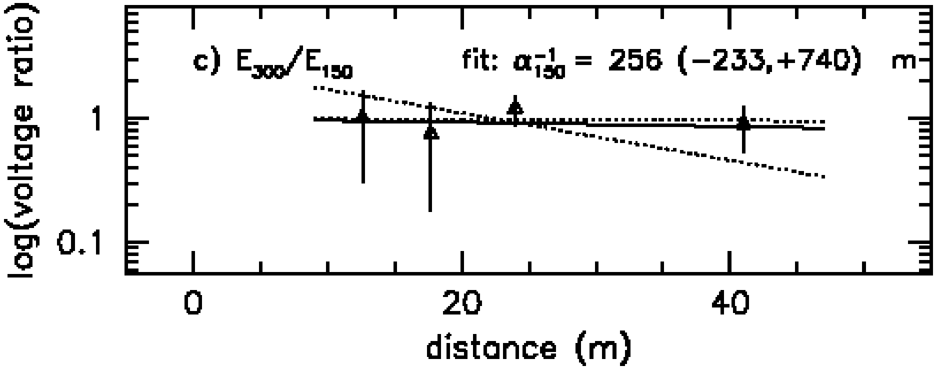
N. Lehtinen et al., PRD 69, 013008 (2004)

Salt Dome Detector Noise and attenuation length measurements

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

Hockley Dome measurements





- 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 ==> 50/yr above 10^{17} eV from AGN
  - 1000 R_X ==> 50/yr above 10^{17} eV from GZK or 5-10 GRB