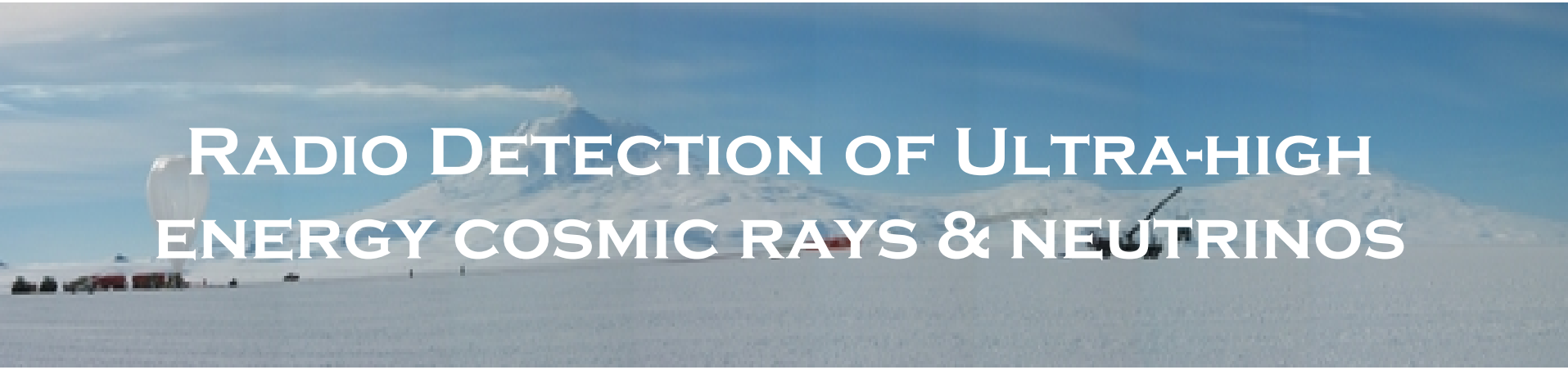


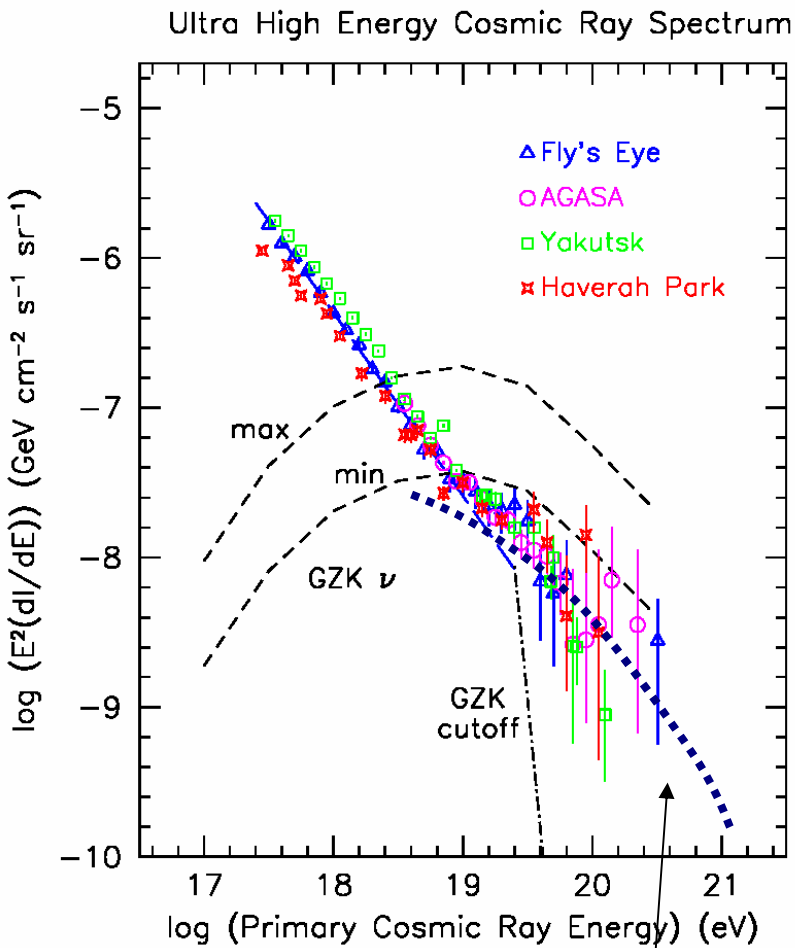
Radio Detection of Ultra-high energy cosmic rays & neutrinos

Peter Gorham

University of Hawaii at Manoa Physics & Astronomy

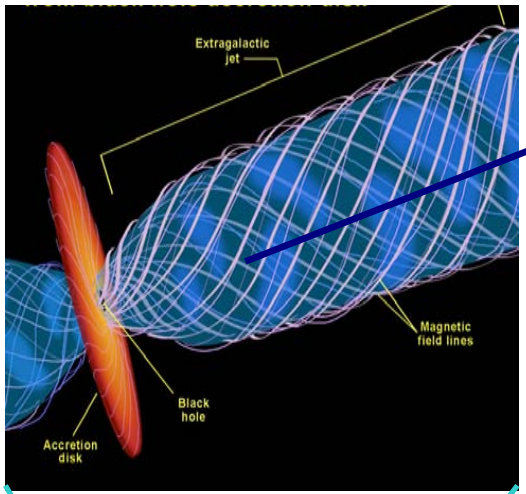
(Ultra-) High Energy Astrophysics of Cosmic rays & Neutrinos

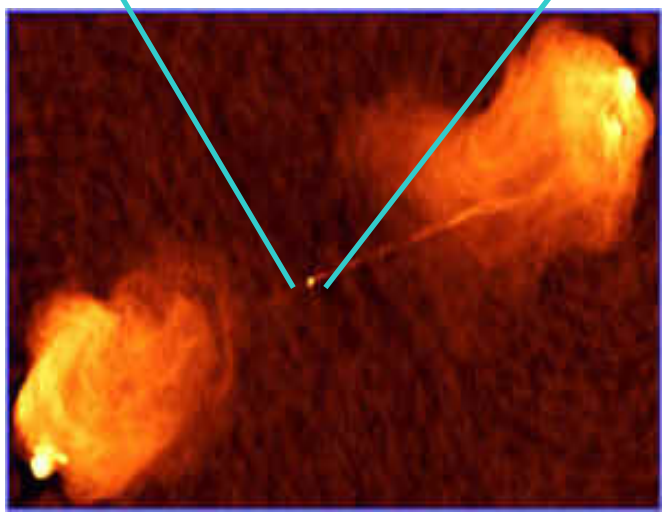
- 40 years of $10^{18\text{-}20}$ eV cosmic ray measurements:
  - Extragalactic, but do we see the GZK absorption edge?
  - pγ interactions at E~1 GeV c.o.m.
    - ==> well known physics!
    - But a Lorentz factor of ~10^{11}…
  - Neutrinos at $10^{17\text{-}19}$ eV guaranteed by GZK process--if we are not in a special part of the universe (standard model)

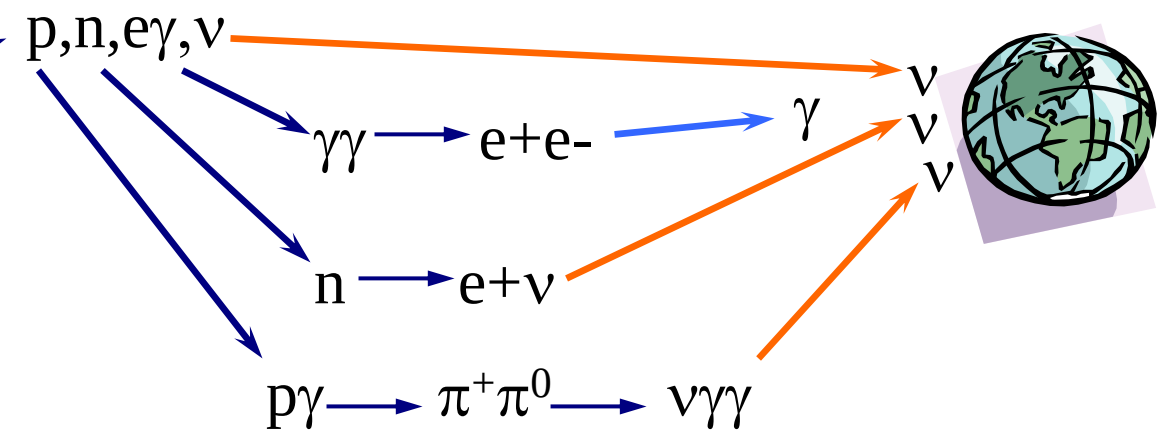


Super GZK
Or pileup?

Role of neutrinos in AGN black hole studies & UHECR

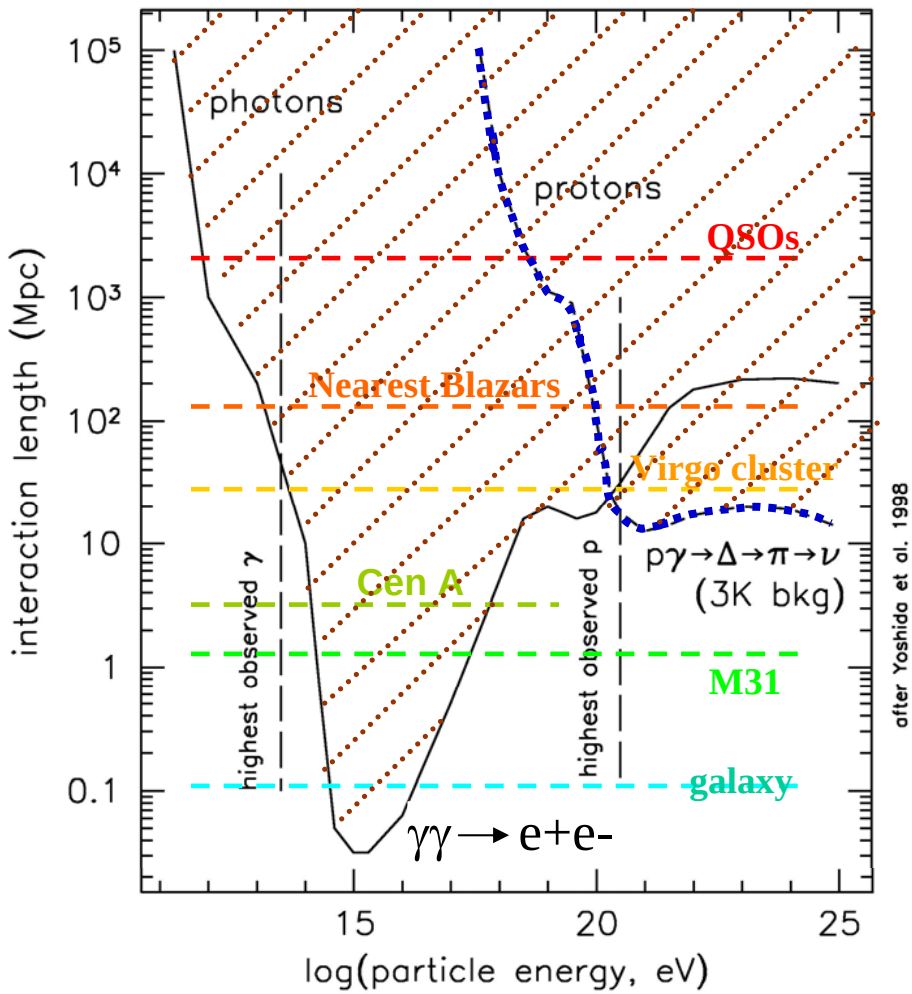






- "Standard model" AGN: black-hole accretion-disk accelerator
- Black holes--QSO engines, accelerate everything in high-density environment
- Neutrinos unattenuated from anywhere: both BH event horizon & GZK propagation process

Neutrinos are all we have at >PeV energies



- Astronomy as we know it ends at ~100 TeV
- Photons absorbed by pair production on IR & μwave background; particles scattered by B-fields or GZK
- But the energetics of the sources clearly extend to ~10^9 TeV or more
- Ergo: we need neutrinos

What do we need for a GZK ν detector?

- Standard model GZK ν flux: <1 per km^2 per day over 2π steradian
  - Interaction probability per km of water: ~0.2%

  ==> 1 cubic km detector: ~0.5 event per year in its fiducial volume

we need a teraton (1000 km^3) target!

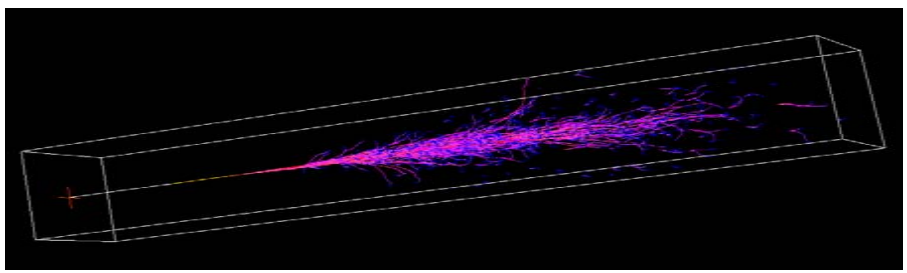
- How do we scale up from current water Cherenkov detectors?

- Answer: Askaryan process: coherent **radio** Cherenkov emission
  - EM cascades produce a charge asymmetry, thus a radio pulse
  - Process is coherent ➔ Quadratic rise of power with cascade energy
  - Neutrinos can shower in radio-transparent media: air, ice, rock salt, etc.
    - ➔RF economy of scale very competitive for giant detectors

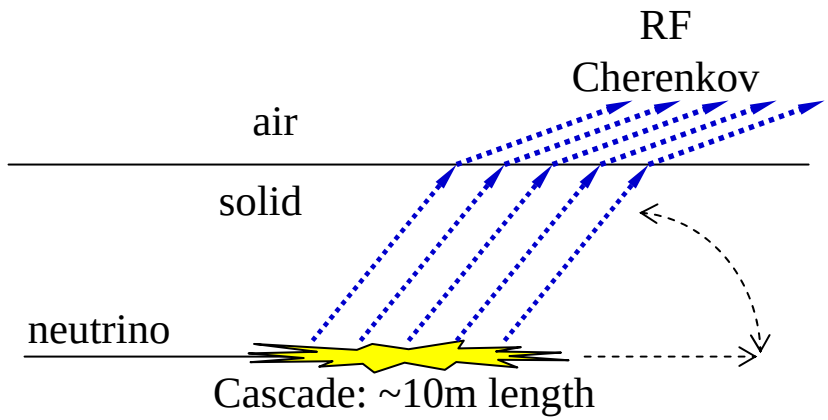
Showers in solid media

Simulation: in rock salt, 0.2-1GHz, 1EeV cascade

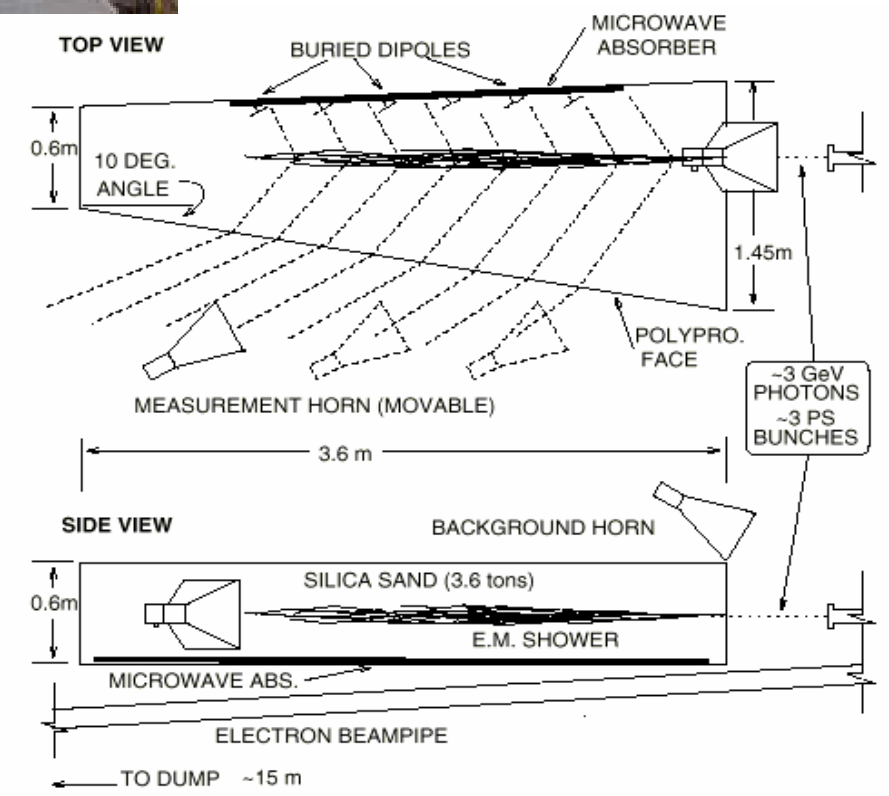
20 m



- Ice: n = 1.78,
  - $\cos^{-1}(1/n) = 53^o$
- Halite (rock salt): n=2.45,
  - $\cos^{-1}(1/n) = 66^o$
- RF Cherenkov cone: propagates through solid, refracts at interfaces



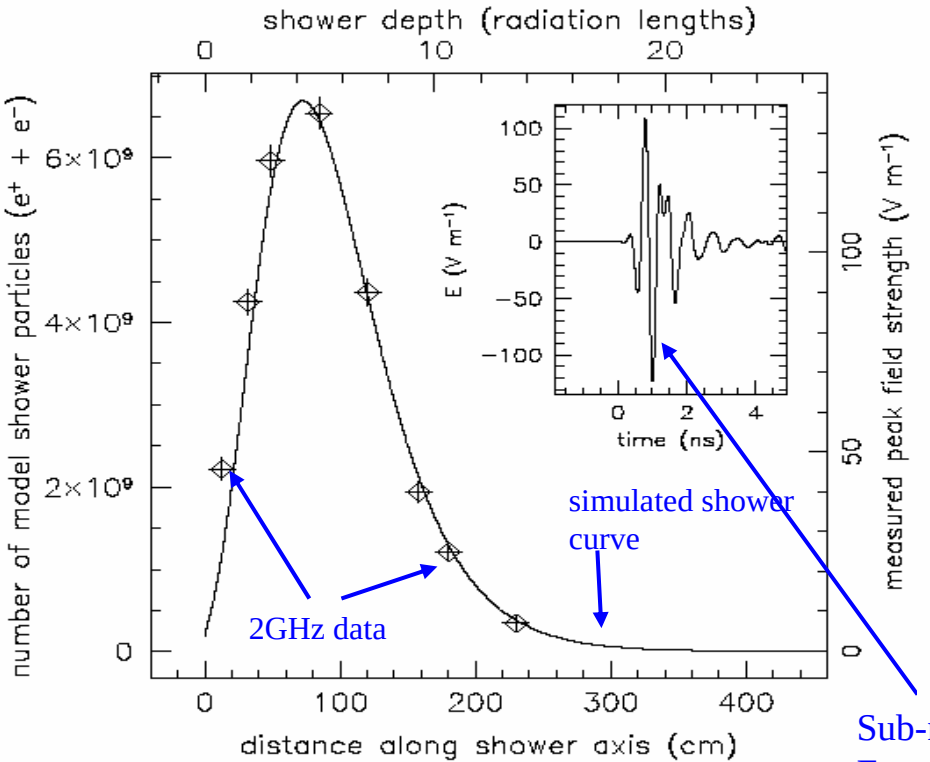
Askaryan Confirmation: SLAC T444 (2000)



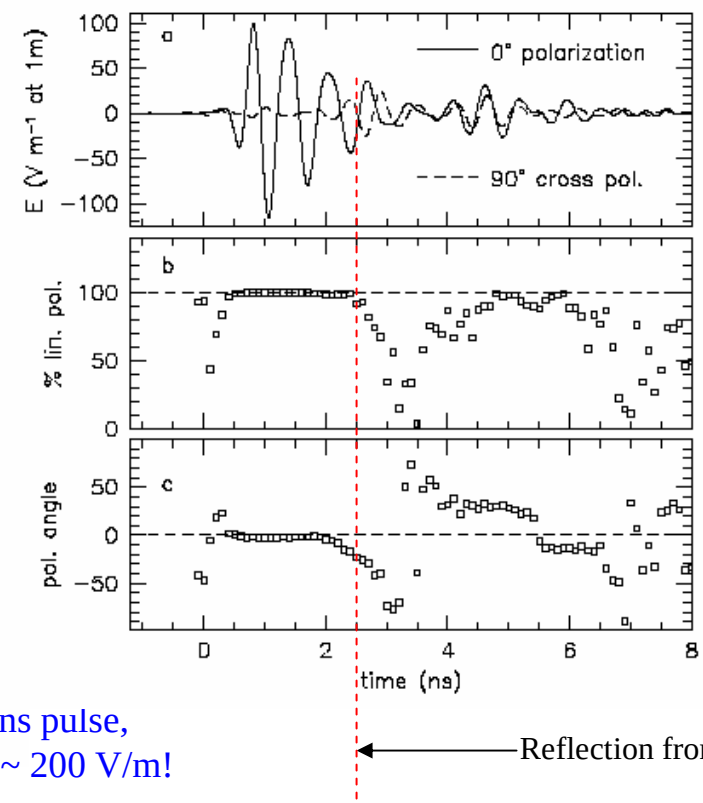
From Saltzberg, Gorham, Walz et al PRL 2001

- Use 3.6 tons of silica sand, brem photons to avoid any charge entering target
  ==> no transition radiation
- Monitor all backgrounds carefully
  - but signals were much stronger!

Shower profile observed by radio (~2GHz)



Sub-ns pulse,
Ep-p~ 200 V/m!



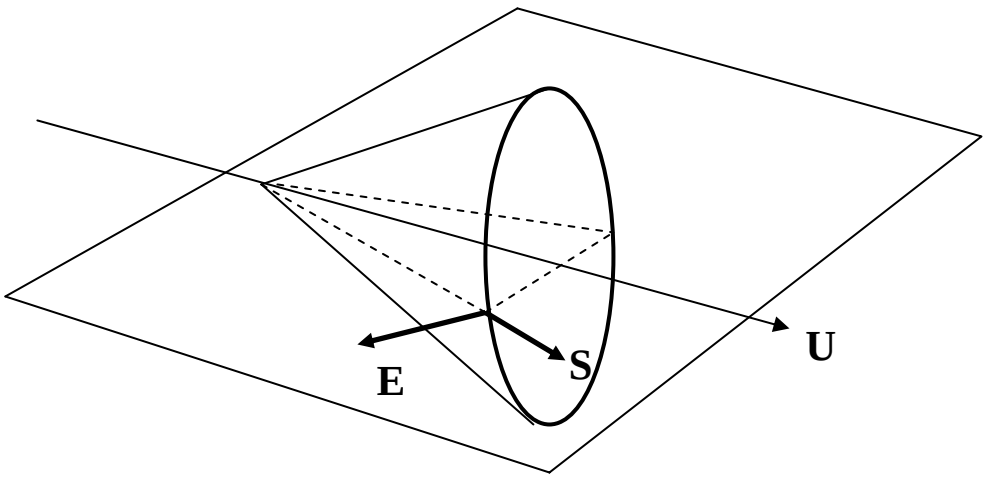
100% polarized

In proper plane

Reflection from side wall

- Measured pulse field strengths follow shower profile very closely
- Charge excess also closely correlated to shower profile (EGS simulation)
- Polarization completely consistent with Cherenkov—can track particle source

Cherenkov polarization tracking

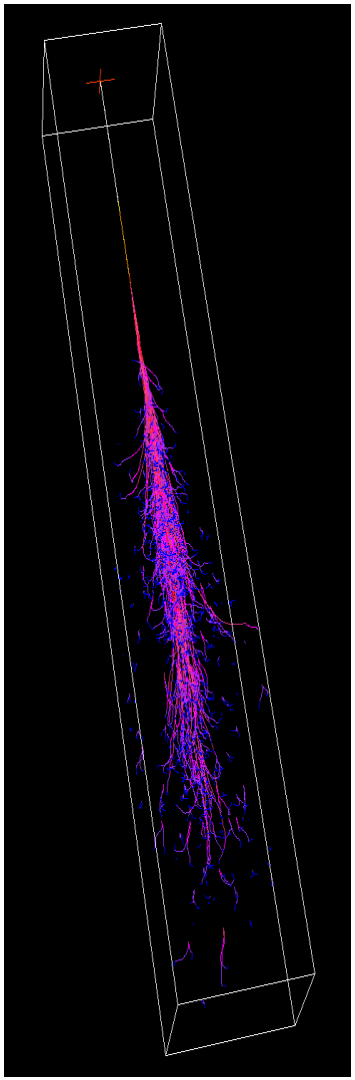


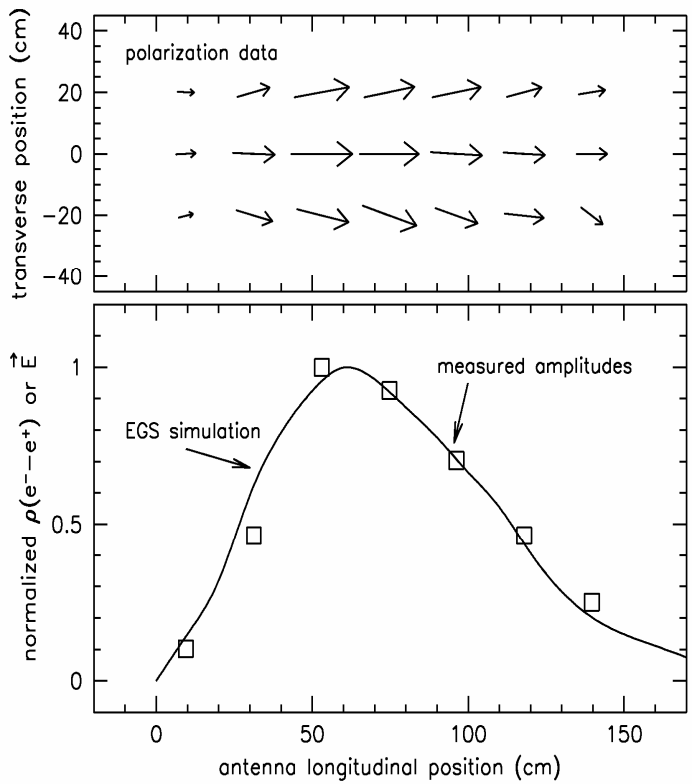
Cherenkov radiation predictions:

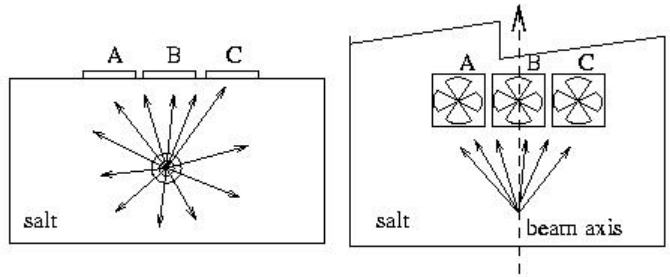
- 100% linearly polarized
- plane of polarization aligned with plane containing Poynting vector **S** and particle/cascade velocity **U**

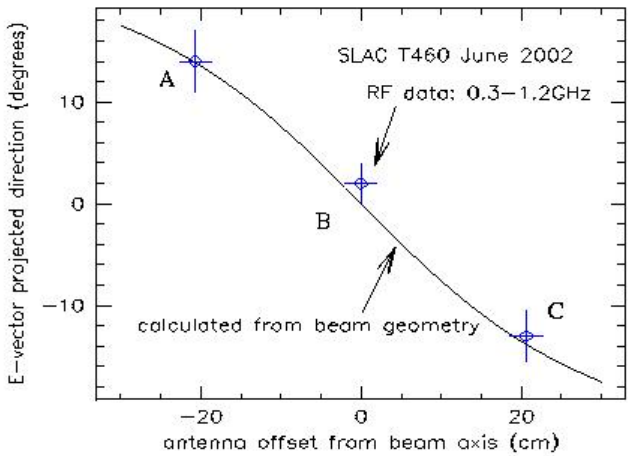
- Radio Cherenkov: polarization measurements are straightforward
- Two antennas at different parts of cone:
  - Will measure different projected plane of E, S
  - Intersection of these planes defines shower track

SLAC T460: Askaryan radiation polarization tracking





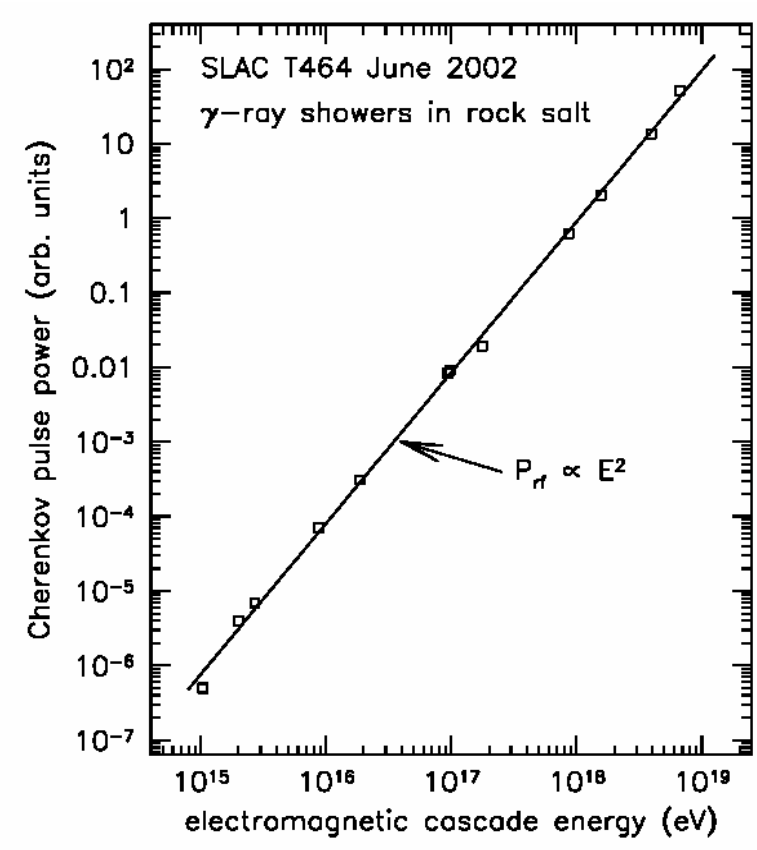




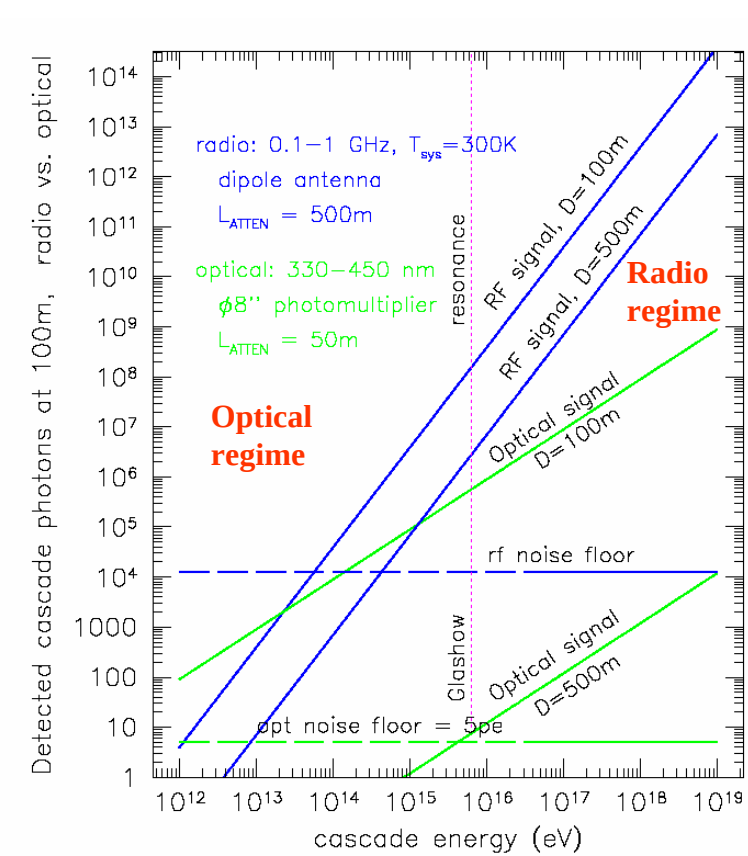
SLAC T460, Gorham et al. 2003

Askaryan process: where does it win?

Huge dynamic range, linearity

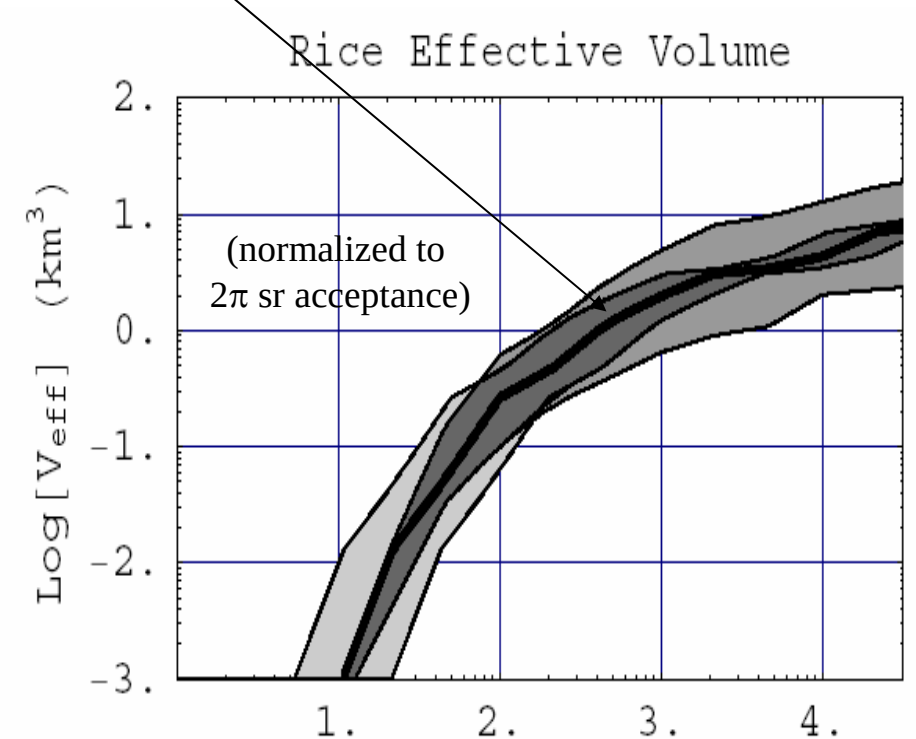


SNR dominant at E >10 PeV

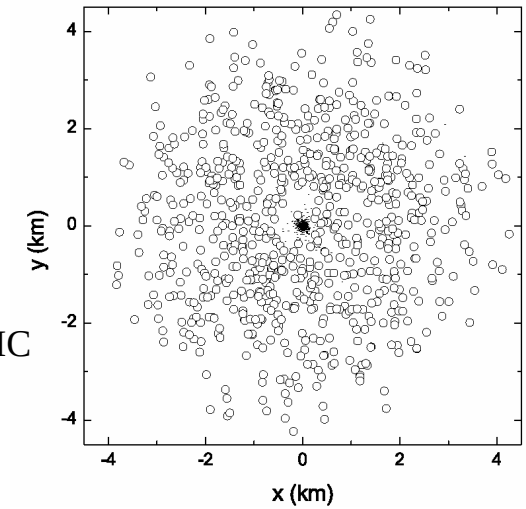


RICE effective volume

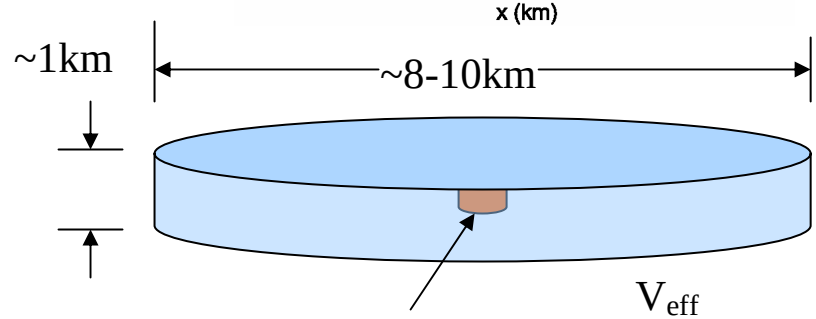
$V_{eff}\,\Omega \sim 6\ km^3\ sr$ @ $E_\nu \sim$1-2 EeV



Log (E_{shower}, PeV) ~ 0.2 E_ν



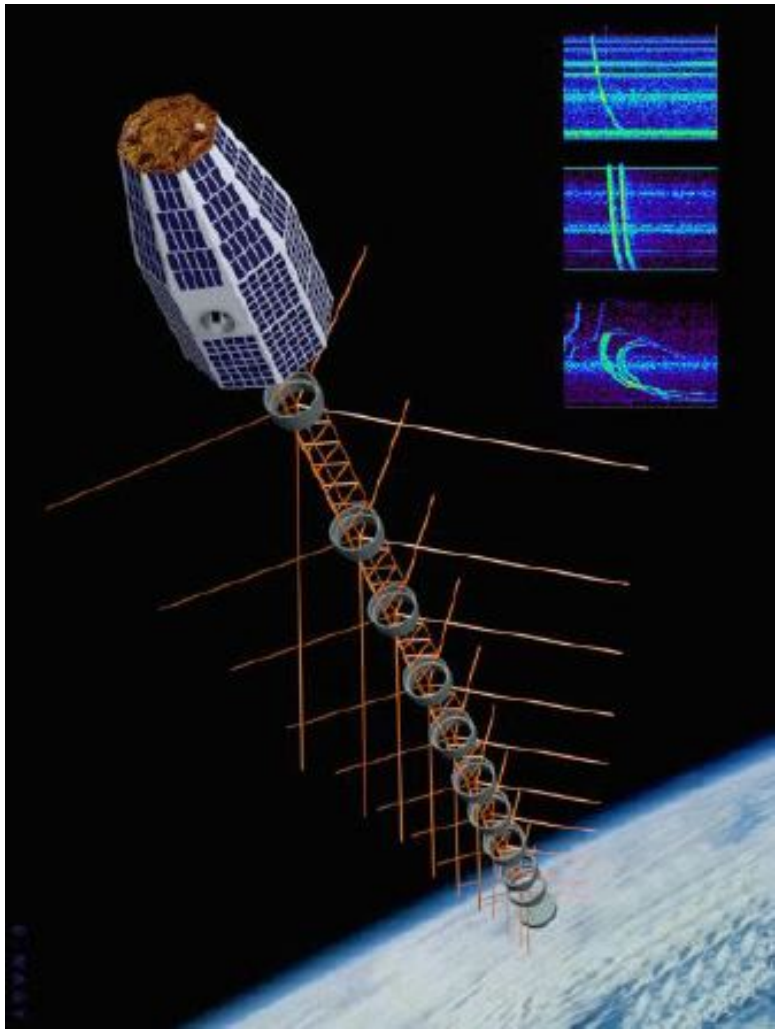
~1 EeV MC vertices



RICE fiducial V ~100m radius

- Large >EeV effective volume based on ice transparency
  - L_{atten} ~ 1km at 300 MHz
- Systematics of ~4-5km horizontal propagation still need study

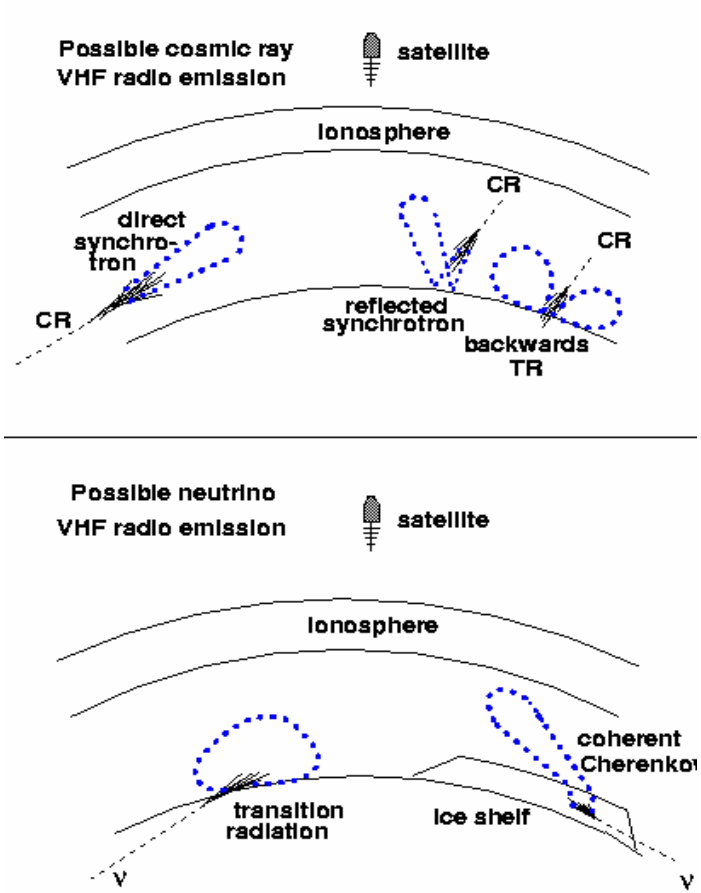
FORTE: A space-based EHE neutrino & cosmic ray detector?

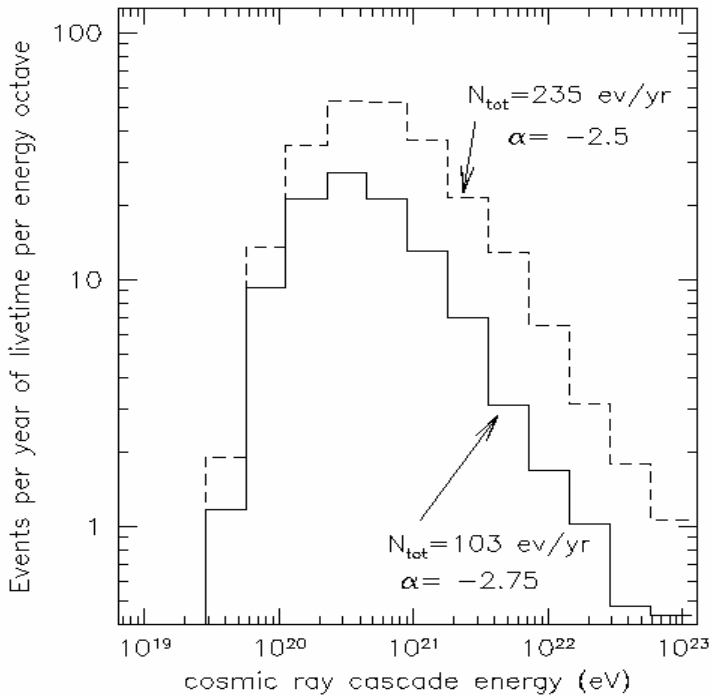


Fast On-orbit Recording of Transient Events

- Pegasus launch in mid-1997, 800km orbit
  - Testbed for nuclear verification sensing
  - US DOE funded, LANL/Sandia ops
  - Scientific program in lightning & related atmospheric discharges
- 30-300 MHz (VHF) frequency range
  - ~3M impulsive triggers recorded to date
- FORTE can trigger on radio emission from giant air showers at E~100 EeV
  - Preliminary estimates: could be ~50 10^{20} eV cosmic ray events in sample
  - Distinct from lightning, could be recognized as isolated events in clear weather regions far from urban noise
  - Analysis (JPL,LANL) planned this year

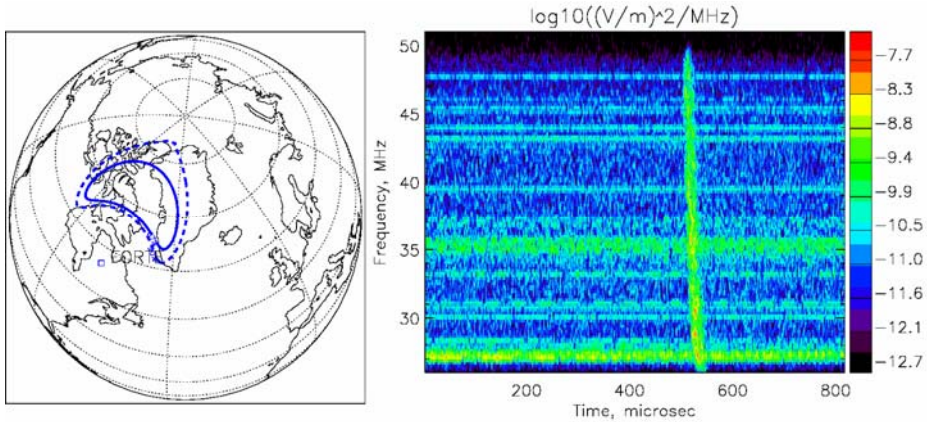
Shower Radio Detection by FORTE

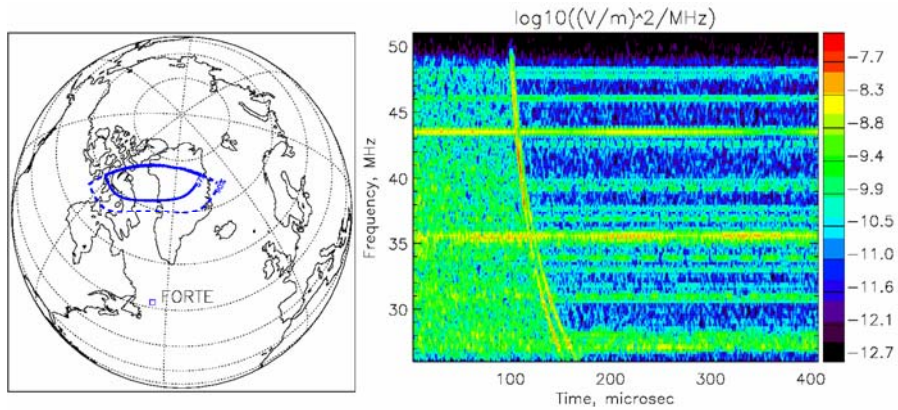


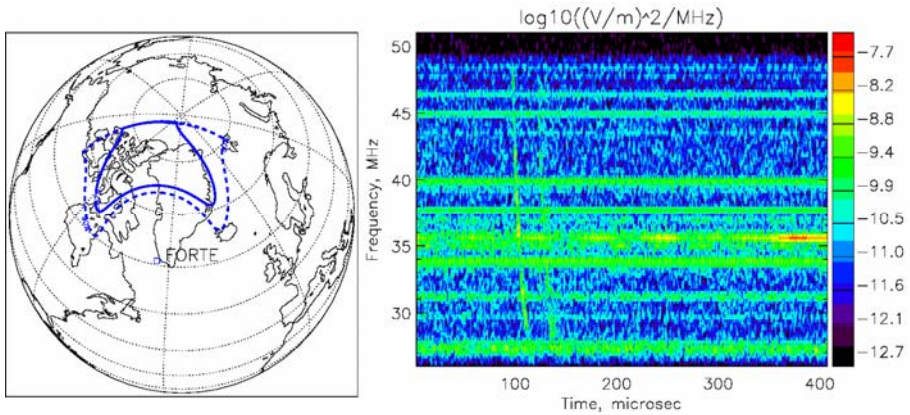


- Simulations indicate that FORTE could be highly sensitive to post-GZK spectrum
- Sensitivity limited by ~10% livetime, RF interference, & uncertainty in radio emission process

FORTE: Lightning events

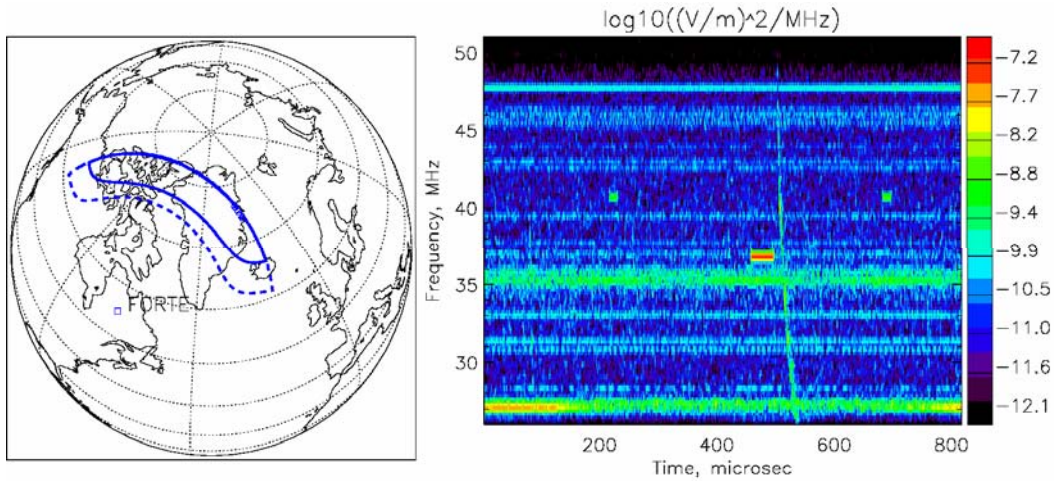


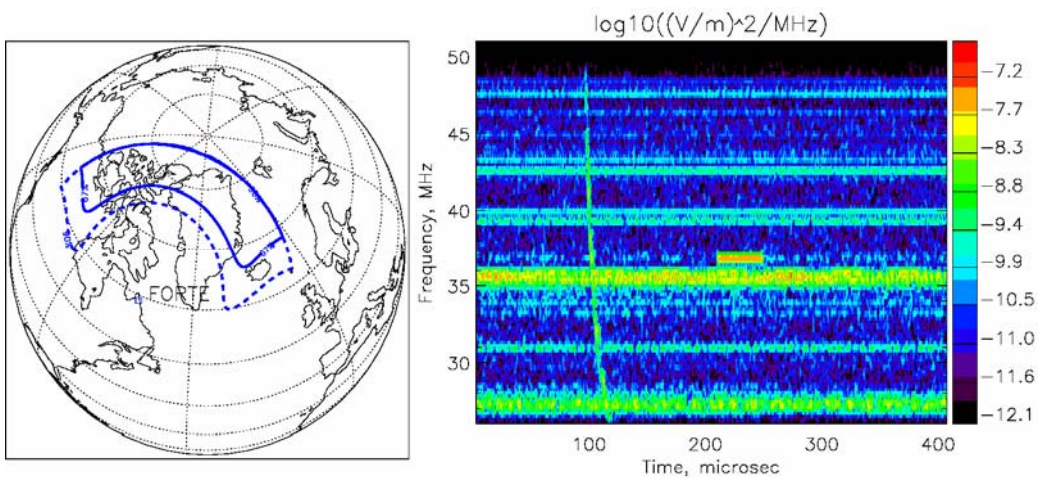




- Satellite can trigger on impulsive events even when strong VHF carrier signals are present
- Plots show Frequency spectrum vs time—curvature on impulses due to ionosphere
  - Aids in geolocation—unique B signature for each satellite position

FORTE: Search for neutrino candidate events from Greenland ice sheet



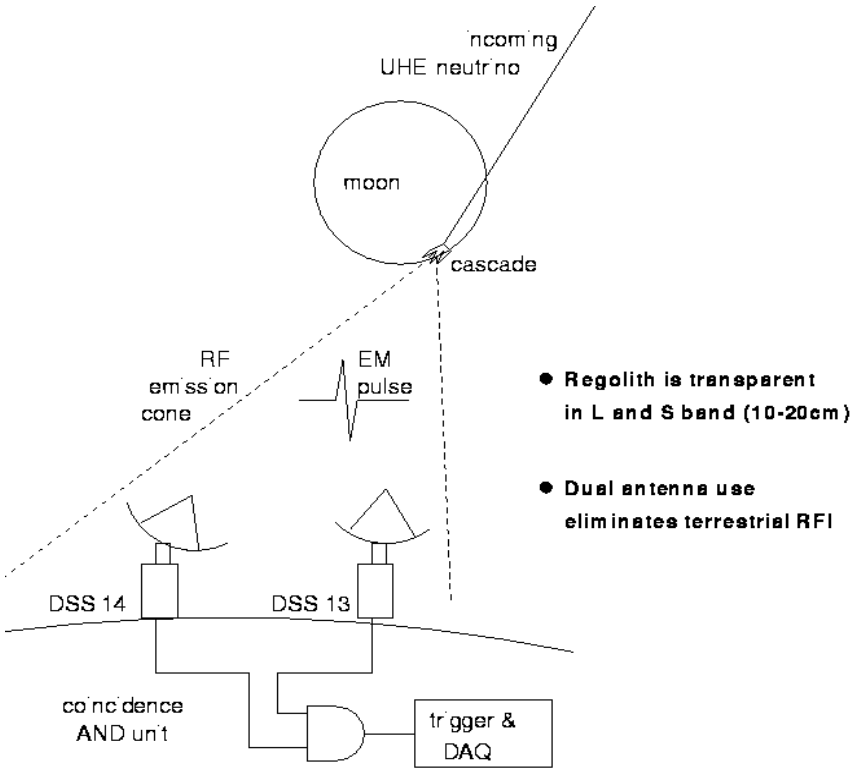


- 3.8 days total livetime
- Threshold high:
  - ~$10^{22.5}$ eV
- 2 candidates survive out of ~2500 initial events
  - Require high polarization, non-lightning, geolocation
- N. Lehtinen, in prep. for PRD 2003

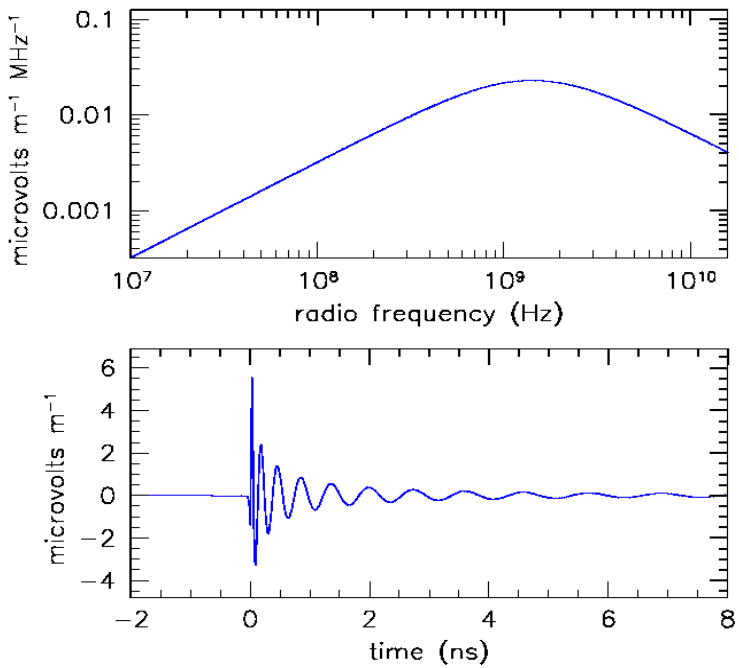
Goldstone Lunar Ultra-high energy neutrino Experiment (GLUE)-- A ZeV example…

- Use NASA Deep Space Network antennas to search for Askaryan pulses from neutrinos interacting in lunar regolith
- Use coincidence to beat RF interference
- Askaryan suggested the moon; I. Zheleznykh ('88) showed we don't have to go there with antennas
- Hankins & Ekers tried with Parkes in 1996

GLUE details



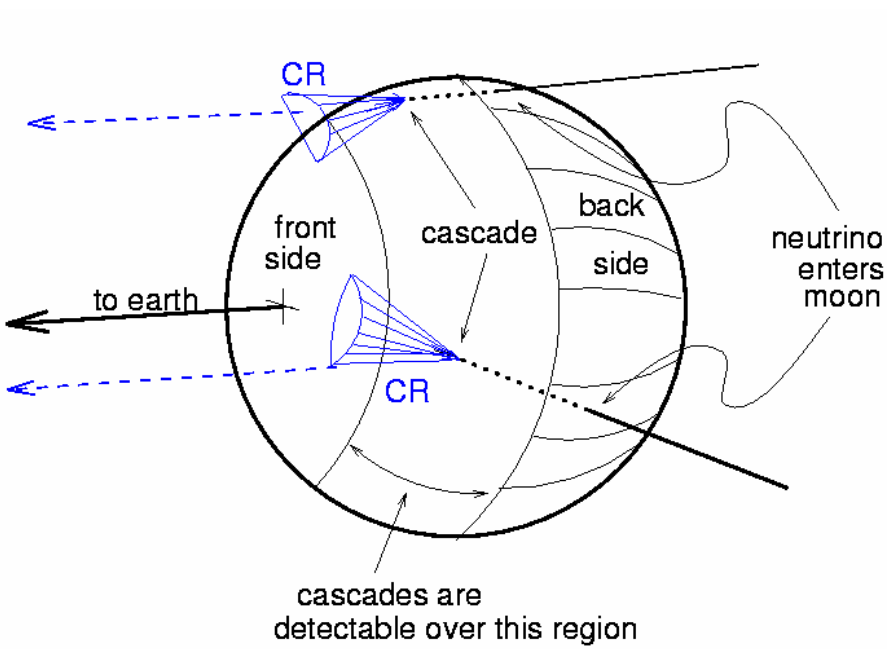
- RF pulse spectrum & shape

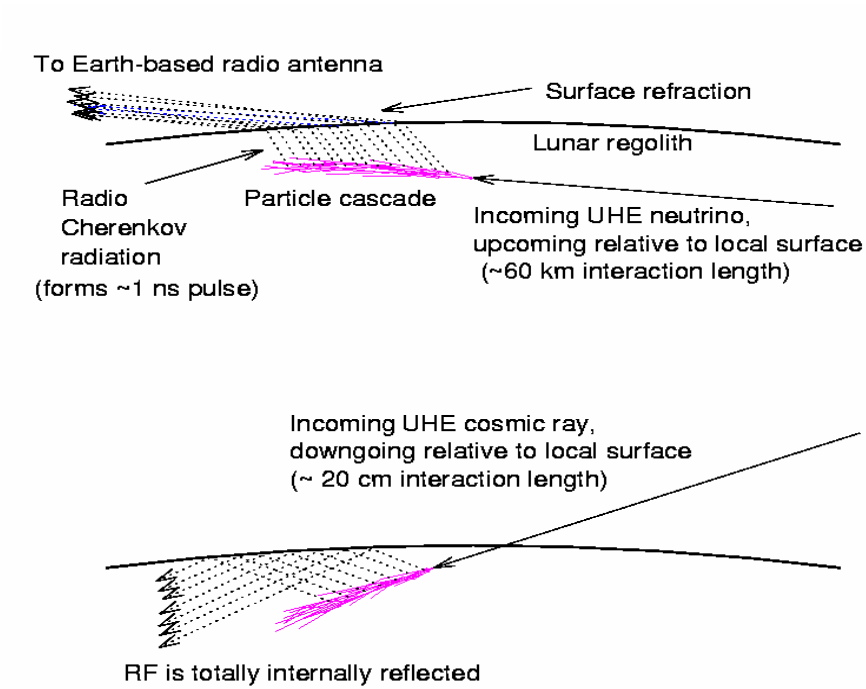


- Effective target volume: Antenna beam (~0.3 deg) times ~10 m moon surface layer

  ===> ~100,000 cubic km!!

Lunar Regolith Interactions & RF Cherenkov radiation



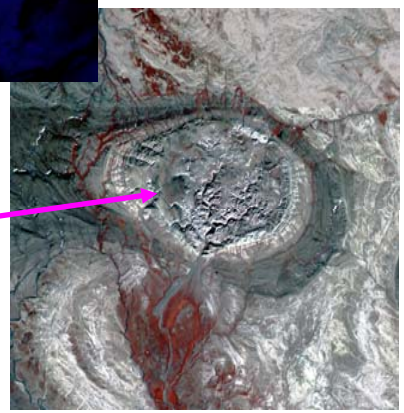


- At ~100 EeV energy, neutrino interaction length in lunar material is ~60km
- R_{moon} ~ 1740 km, so most detectable interactions are grazing rays, but detection not limited to just limb
- 120 hours of livetime to date in 3 years (competes with spacecraft telecom)

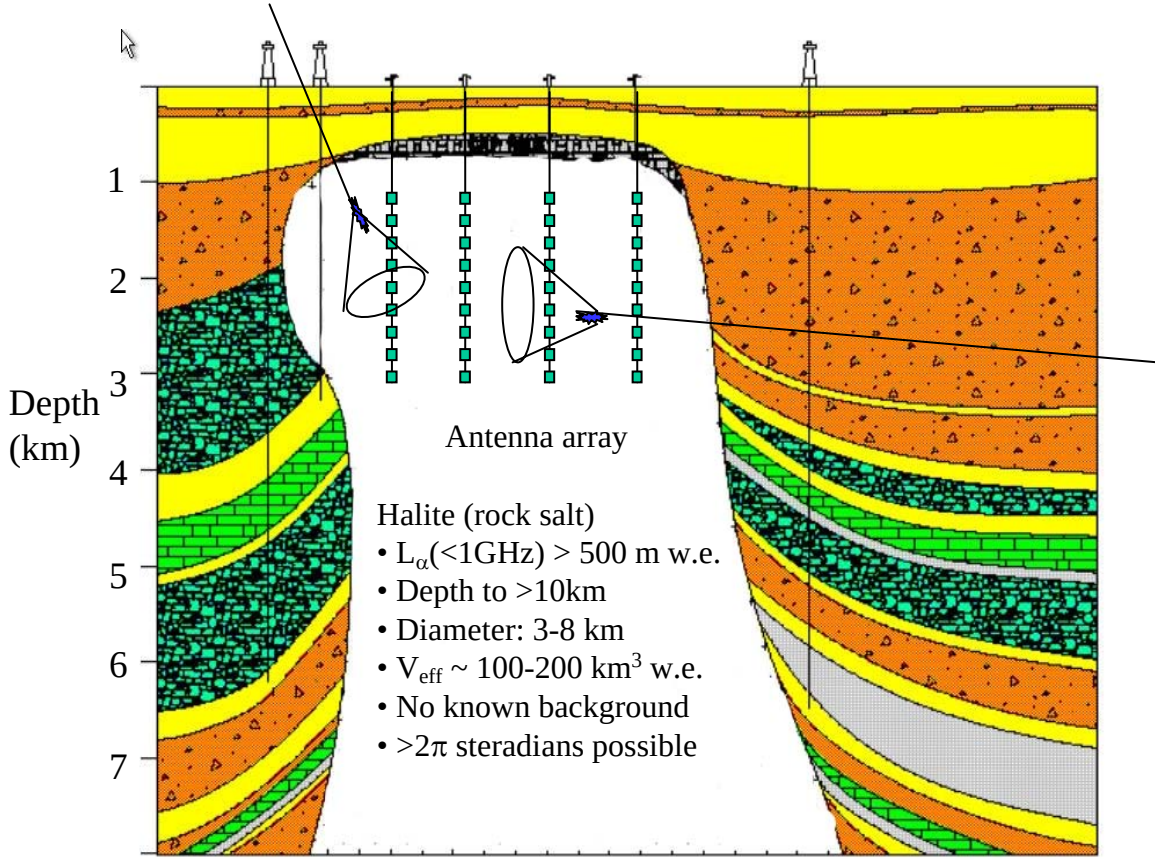
Saltdome Shower Array (SalSA) concept

Salt domes: found throughout the world

Qeshm Island, Hormuz strait, Iran, 7km diameter

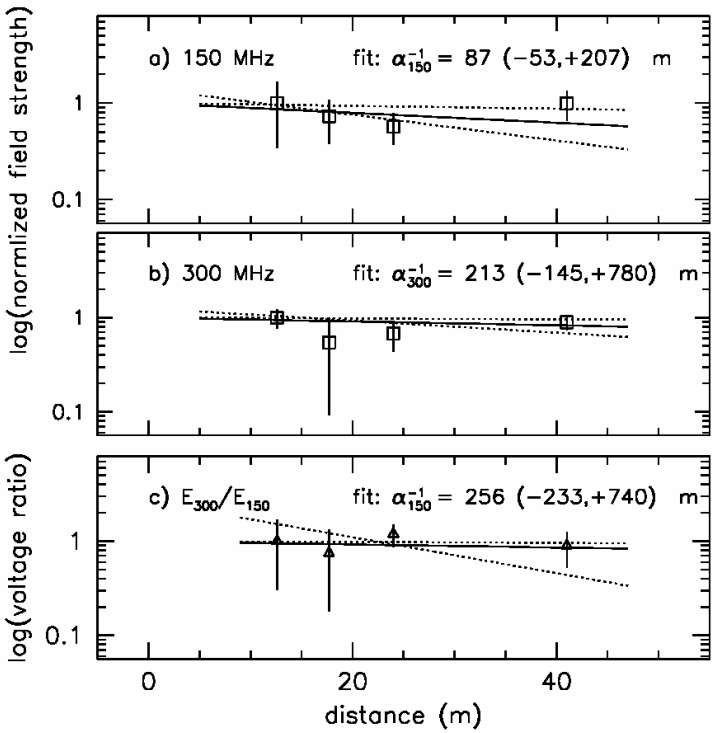


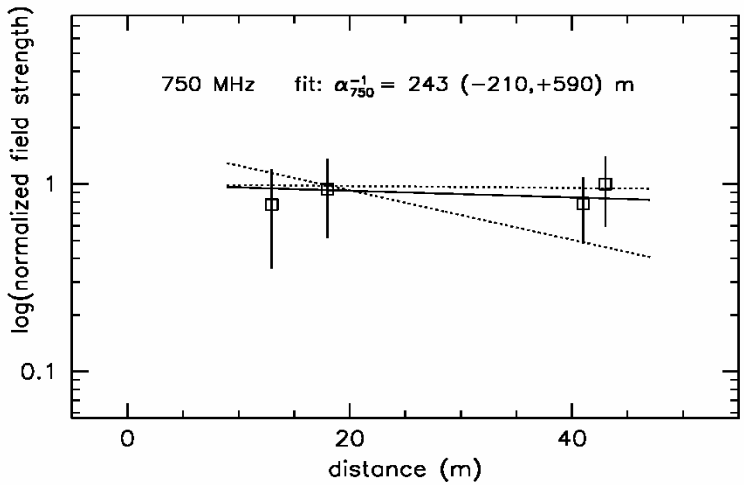
Isacksen salt dome, Elf Ringnes Island, Canada 8 by 5km



- Rock salt can have extremely low RF loss: ➔ as radio clear as Antarctic ice
- ~2.4 times as dense as ice
- typical salt dome: **50-100 km^3** water equivalent in top ~3km

2001 Hockley salt dome rock salt tests

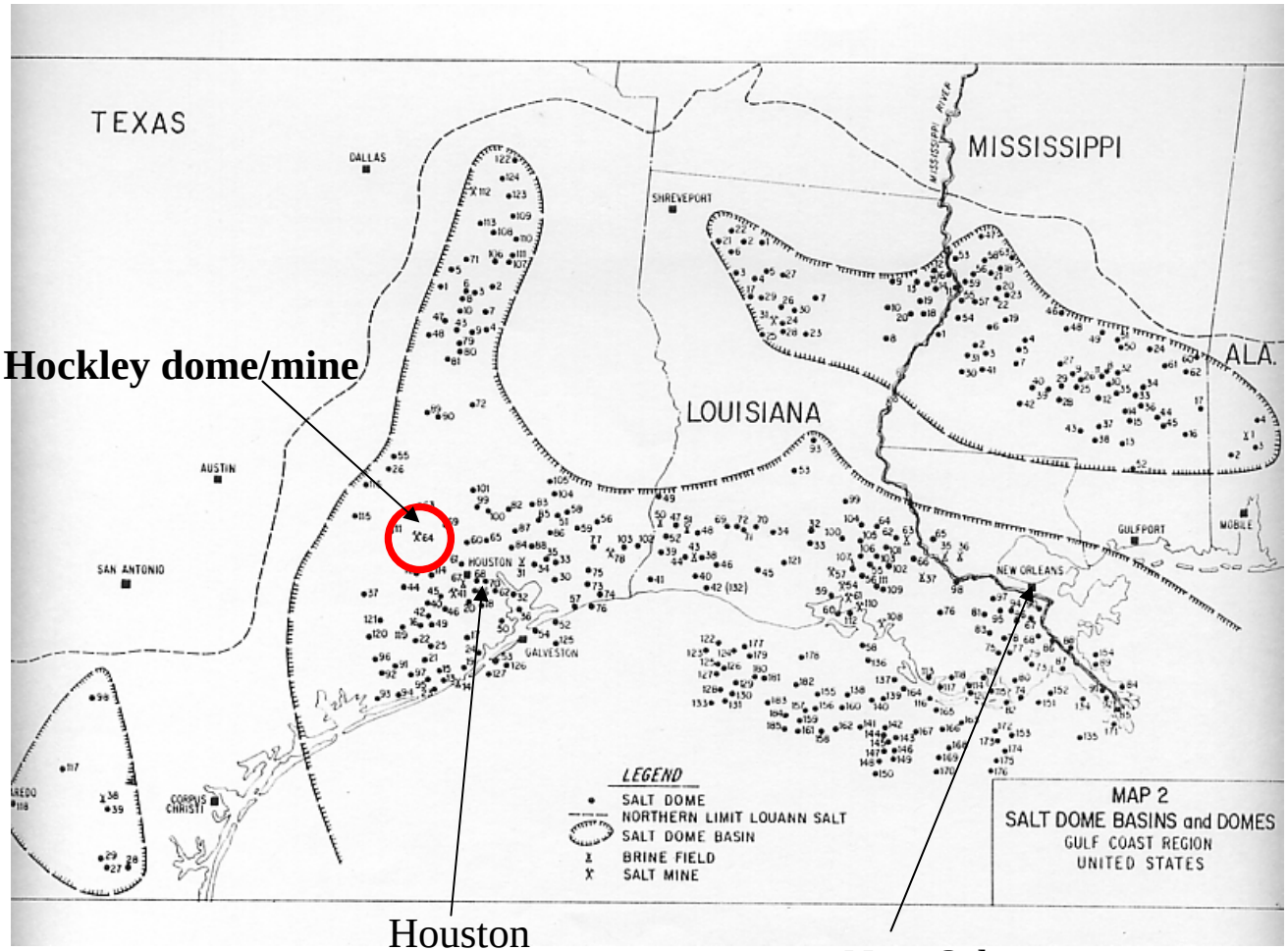




Gorham et al. NIM 2002

- 150, 300, 750MHz all consistent with >200 meter attenuation lengths
- Supported by ground-penetrating radar results since early 1970's
  - Radar pulses sent through ~3 km of salt in some Gulf-coast salt domes

U.S Gulf coast salt domes



Hockley dome/mine

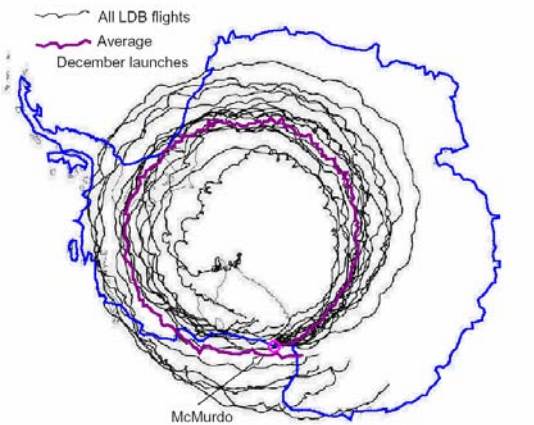
Houston

New Orleans

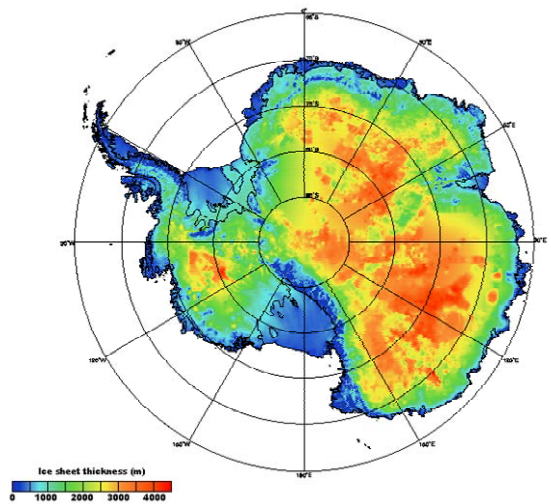
Salt dome demographics:

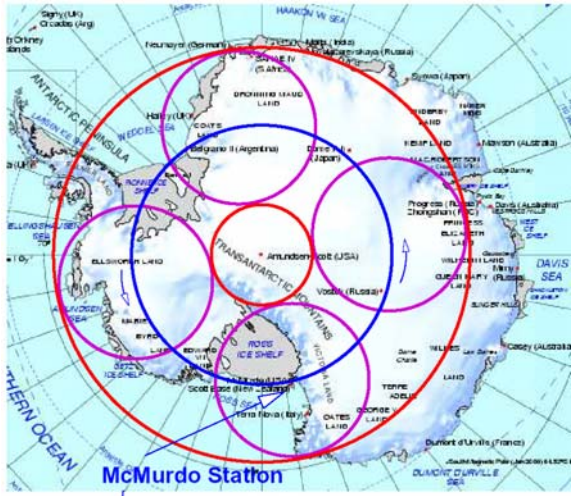
- Several hundred known—some are good source of oil
- Typical ~3-5 km diameters, 5-15 km deep
- **~200 km^3 water equiv. in top 3-5 km for many domes**

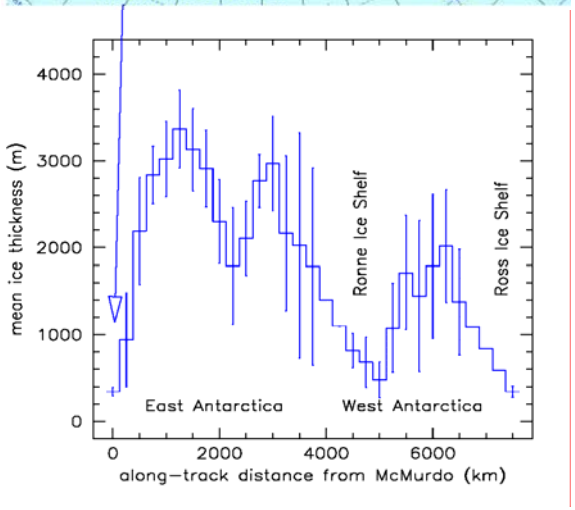
ANITA Mission Design



Parameter	*value*
Launch dates & flexibility	12/06-1/07, 12/07-1/08, 12/08-1/09
Mission duration	15 days each flight, 45 days total
Orbit type	Circumpolar Antarctic Balloon
altitude	25-40 km
latitude	nominally 78° S Latitude
latitude range	73-82° S Latitude
launch vehicle	Long-duration He gas-filled balloon

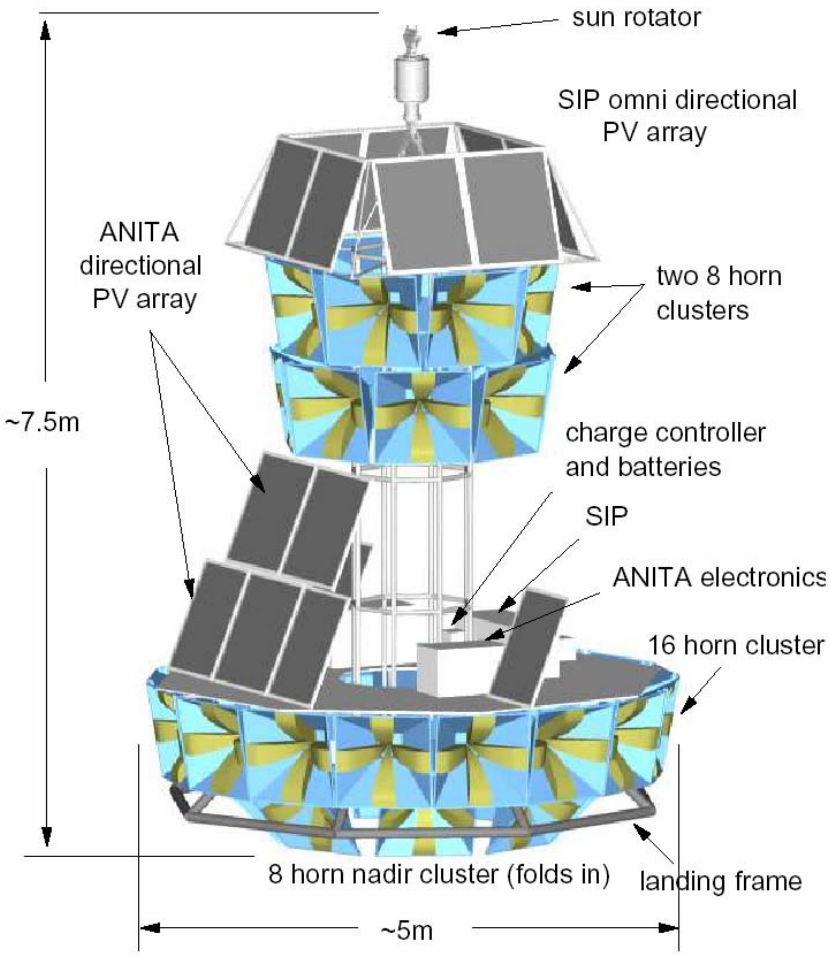


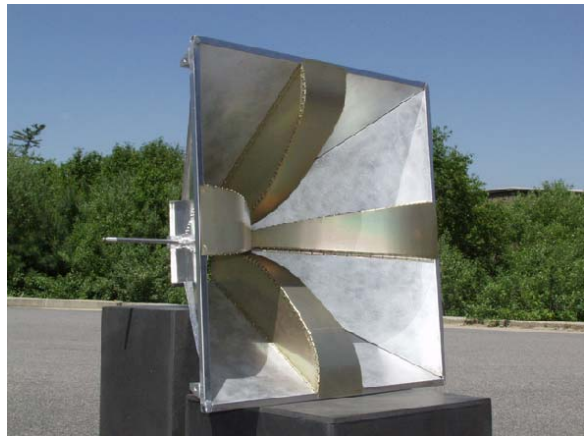




- ANITA depends uniquely on Antarctica
- Balloon altitude nearly optimal
- Ice thickness avg = 1500m under typical LDB track

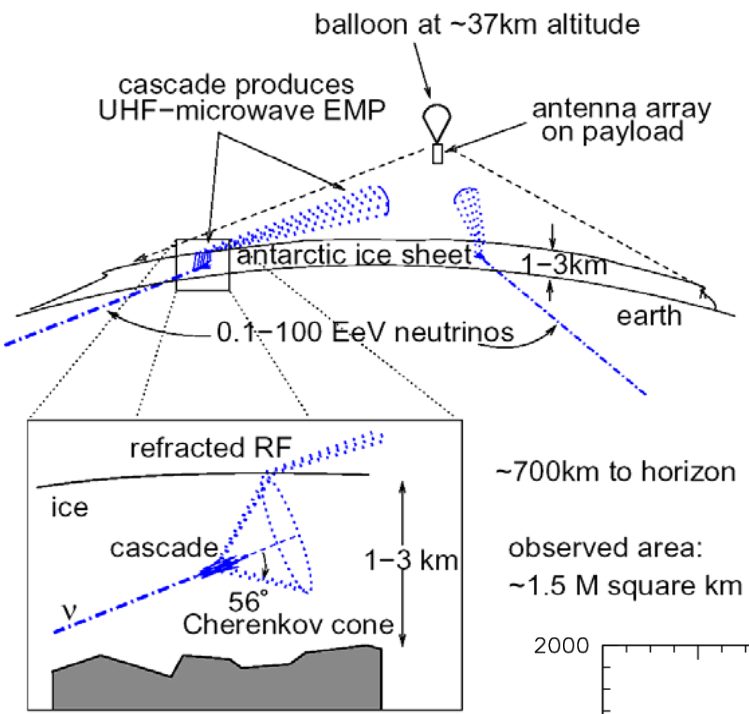
Mission & Flight Payload Design

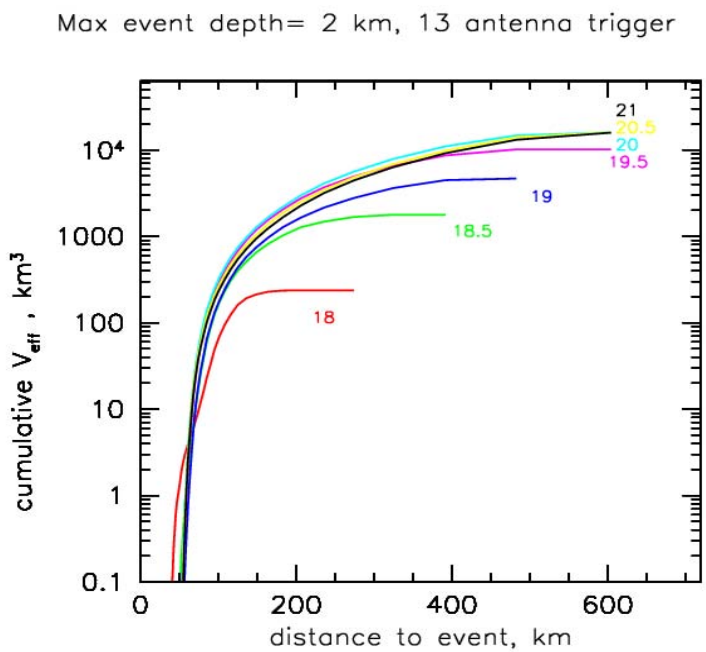


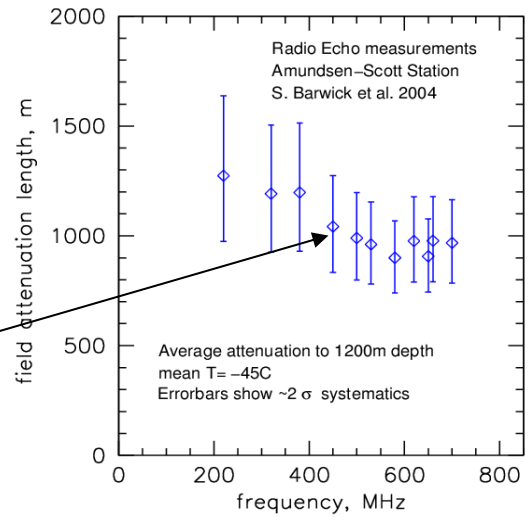


- Quad-ridged horn antennas provide superb impulse response & bandwidth
- Interferometry/beam gradiometry from multiple overlapped antenna measurements

ANITA concept & basis







Ice RF clarity: ~1km(!) atten. length

Effective "telescope" aperture (km^3 sr):

- ~250 @ 10^{18} eV
- ~10^4 @ 10^{19} eV

(compare to ~1km3 at lower E)

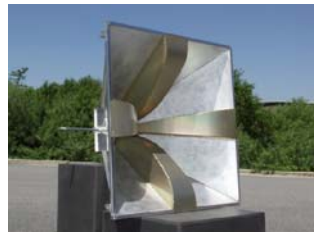
ANITA-lite EMI balloon survey

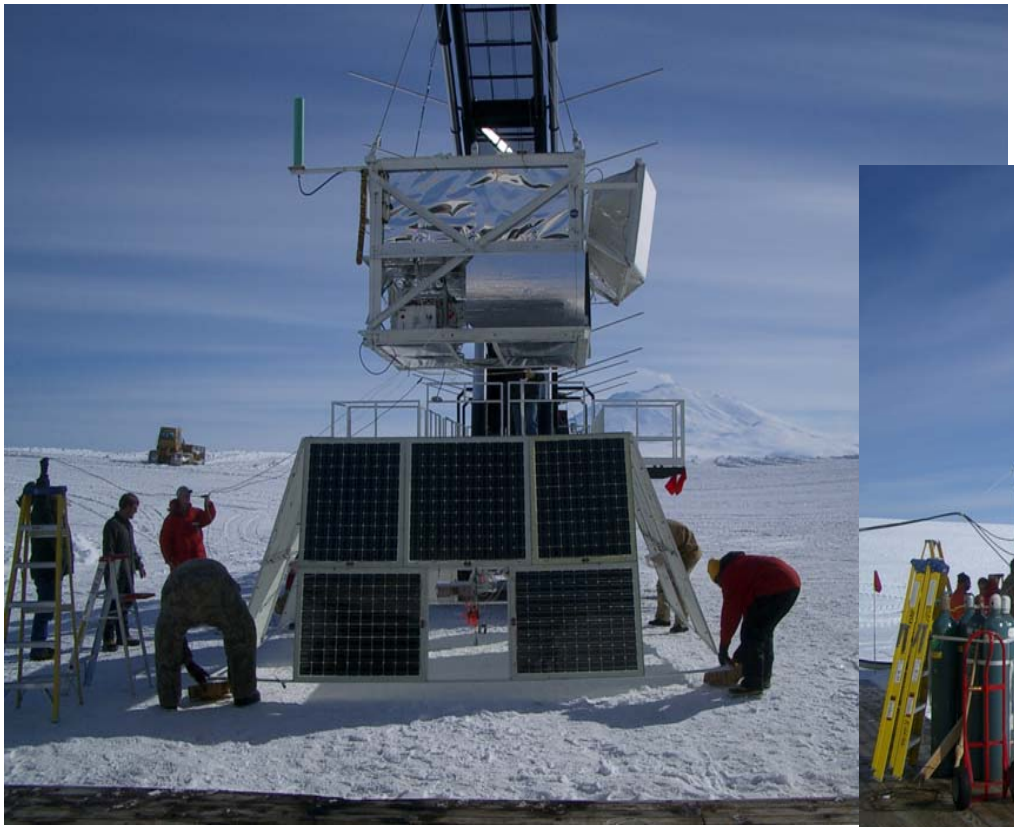
NASA provided a piggyback mission of opportunity for ANITA On the '03-'04 Trans-Iron Galactic Element Recorder (TIGER) flight…

- ANITA-lite flew ANITA prototypes & OTS hardware
  - 2 dual polarization prototype ANITA antennas
  - 4 channels total at 2 GHz sampling, 1 GHz bandwidth

- Measured ambient RF interference & thermal noise
- 18 days flight time, 130K events recorded
- External drive recovered w/ 80% of data
  - 20% still in cold storage, awaiting instrument recovery
- Results look excellent so far…

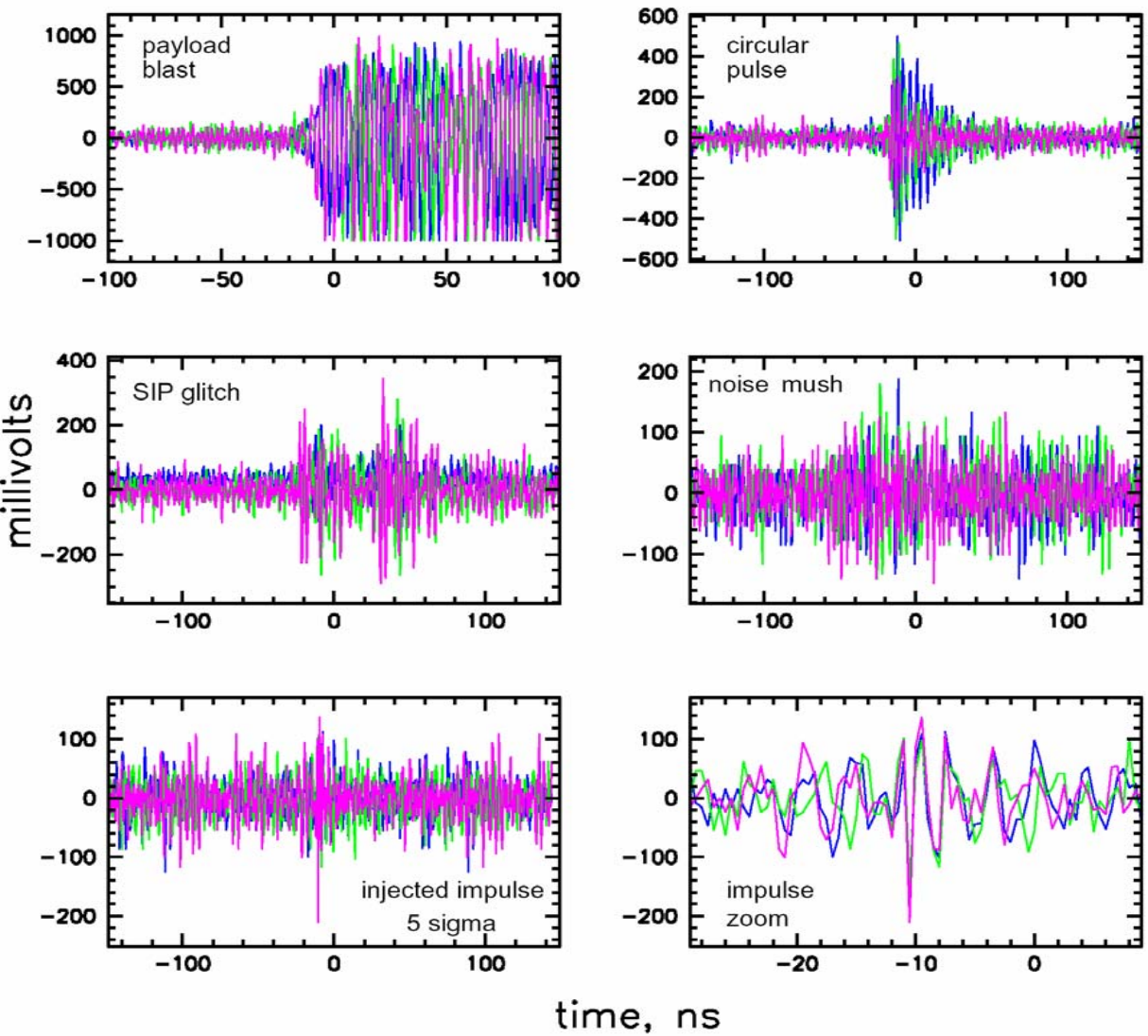
TIGER/ANITA-lite launch preparation





TIGER ANITA-lite launch

ANITA-lite impulse analysis



- **Dominated by payload local noise**
- Circularly polarized impulses (TDRSS relay turn-on?) are closest to true impulses (but not)
- Glitches from balloon support package (charge controller MOSFETS)
- Injected 3 and 5 sigma signals (overlain on actual thermal noise) used to test algorithm efficiency
- Accidental rate: 3-fold, 5 sigma:
  - < 1 per week

Impulse analysis (cont.)

- Impulse cuts:
  - Power at trigger/power in tail > 1.6
  - Risetime of highest V peak < 3ns
  - Cross correlation with known impulse response improves SNR
  - Power in tail / power in pre-trigger noise < 2

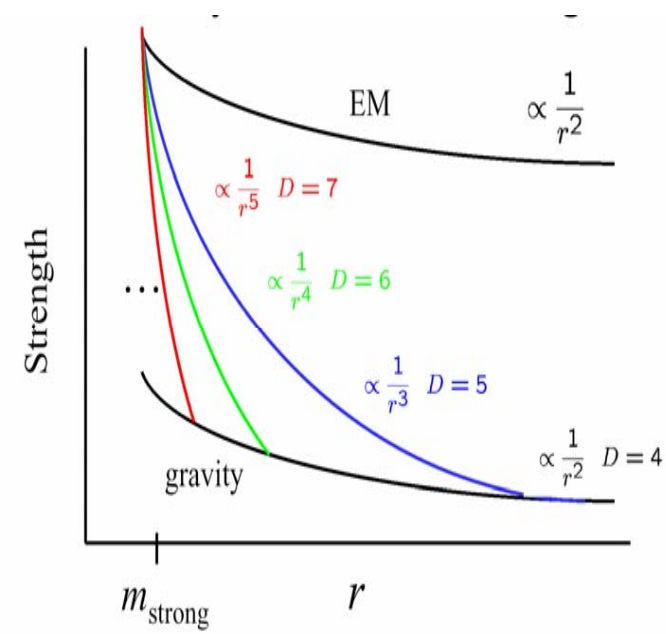
Total: 97163 events	Ch1	Ch2	Ch4	Ch1+ch2	Ch2+ch4	3-fold
data	713	466	596	11	6	0
Pre-trigger noise	94	103	71	0	0	0
3 sigma impulse	60993	50918	62696	32744	33468	21683
5 sigma impulse	86122	82723	87233	73594	74511	66358

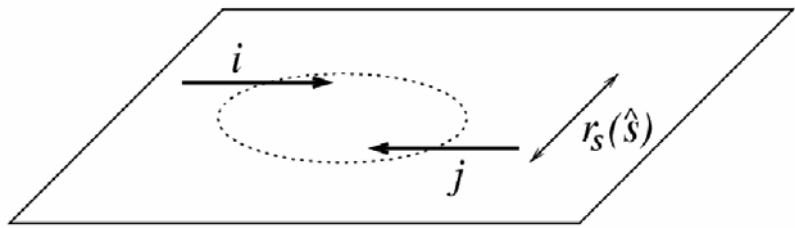
BKG rejection: 100%

SIG efficiency: ~70%

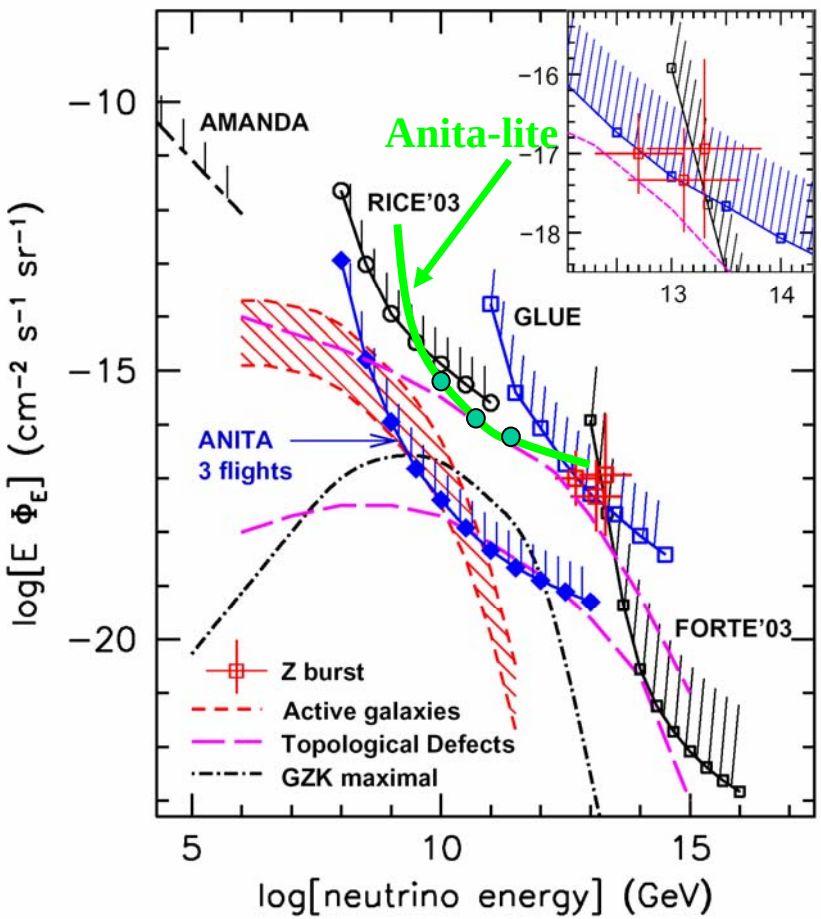
Antarctic Black Hole factory?

- Suppose that photons are confined to 4-space, D=4
- But gravity propagates in n extra dimensions of size L
- For r>>L, $F_{grav} \sim r^{-2}$, but r<<L, $F_{grav} \sim r^{-(2+n)}$
- Now: particle collisions can make a black hole (BH) if $E_{cm} > m_{strong}$
- For D=4+n, $m_{strong} \sim$ TeV is possible!
- For GZK neutrinos on protons
  - $E_{cm} \sim 100$ TeV
  - ==> GZK neutrinos can make BH with up to 2 order of mag higher cross section than standard model neutrinos
  - Will immediately decay & shower
- Anita-lite may constrain highest predictions!





ANITA/ANITA-lite sensitivity (preliminary)



- Approximately 18 days of data, net 40% livetime ==> 1 week
- Simulation threshold ~ 5 sigma per channel
- No candidates survive impulse cuts
- ~65% of 5 sigma injected signals survive
- If signal were at **GLUE/RICE** limits, ANITA-lite sees ~10-20 events
  - Highest TD model probably excluded
- **RICE** limits for 3500 hours livetime
- **GLUE** limits ~120 hours livetime
- **FORTE** (N Lehtinen, UH) limits on ~3 days of satellite observations of Greenland ice sheet
- ANITA sensitivity:
  - ν_μ & ν_e included, full-mixing parameterized
  - 1.5-2.5 orders of magnitude gain

Summary

Radio detection: The most cost-effective way to do PeV (10^{15} eV) to ZeV (10^{21} eV) astronomy

UHE neutrino models already constrained by existing detectors

ANITA-lite 2003: most sensitive EeV to date!?

ANITA 2006: the GZK BH factory?!