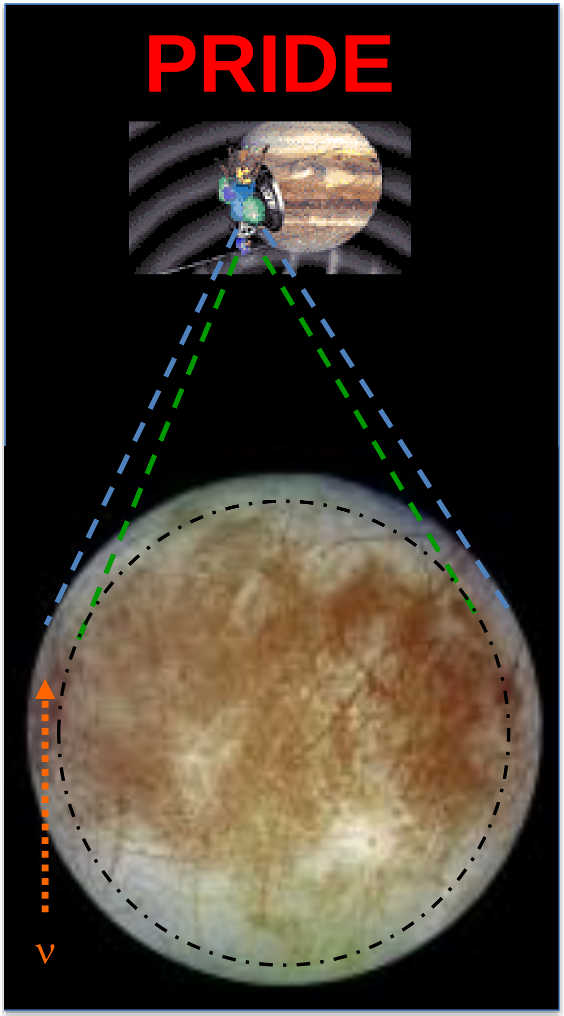


PRIDE – Passive Radio Ice Depth Experiment - An Instrument to Measure Outer Planet Lunar Ice Depths from Orbit using Neutrinos

Tim C. Miller
Robert Schaefer
H. Brian Sequeira
G. Wesley Patterson

Johns Hopkins University Applied Physics Laboratory
11100 Johns Hopkins Rd, Laurel, MD 20723
Robert.Schaefer@jhuapl.edu

The Johns Hopkins University Applied Physics Laboratory
Civilian Space

The Johns Hopkins University Applied Physics Laboratory
National Security Space

APL
JOHNS HOPKINS UNIVERSITY
Applied Physics Laboratory

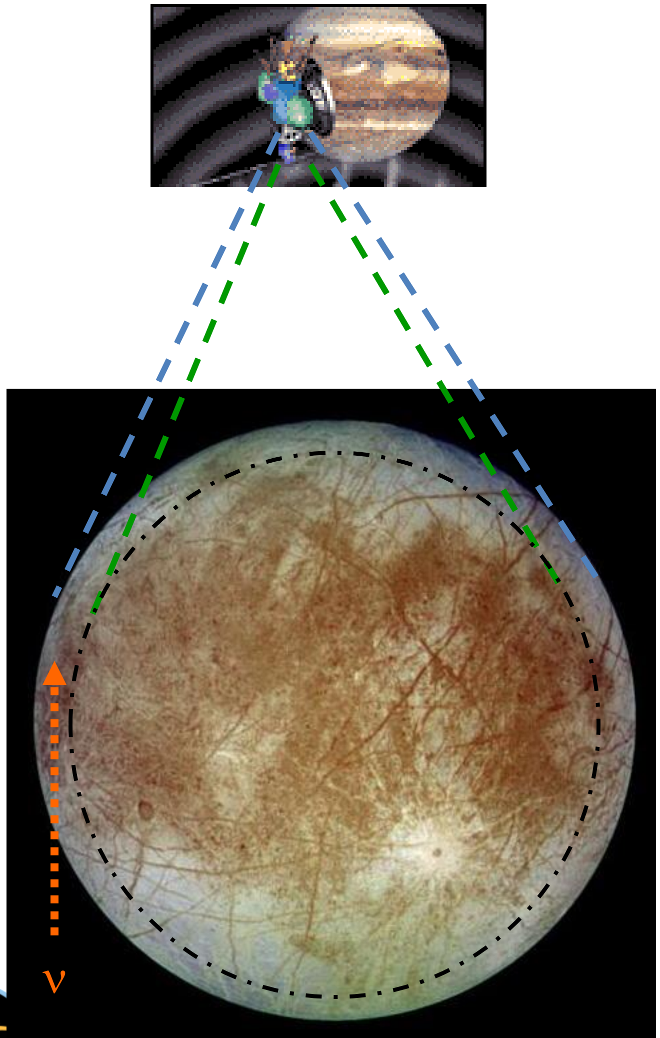
Overview

- Investigated a technique for remotely sensing ice depths on icy moons
  - Using cosmic neutrino "illumination"
  - Using passive RF technology on the satellite
- Performed a high level feasibility study of an outer planet mission instrument ("PRIDE").
- No major showstoppers found, but a deeper analysis is required to fully define the instrument design and derive a realistic observing strategy

PRIDE (Passive Radio [frequency] Ice Depth Experiment): An instrument to passively measure ice depth from a Europan orbiter using neutrinos
Timothy Miller, Robert Schaefer, H. Brian Sequeira

Icarus 220 (2012) 877–888

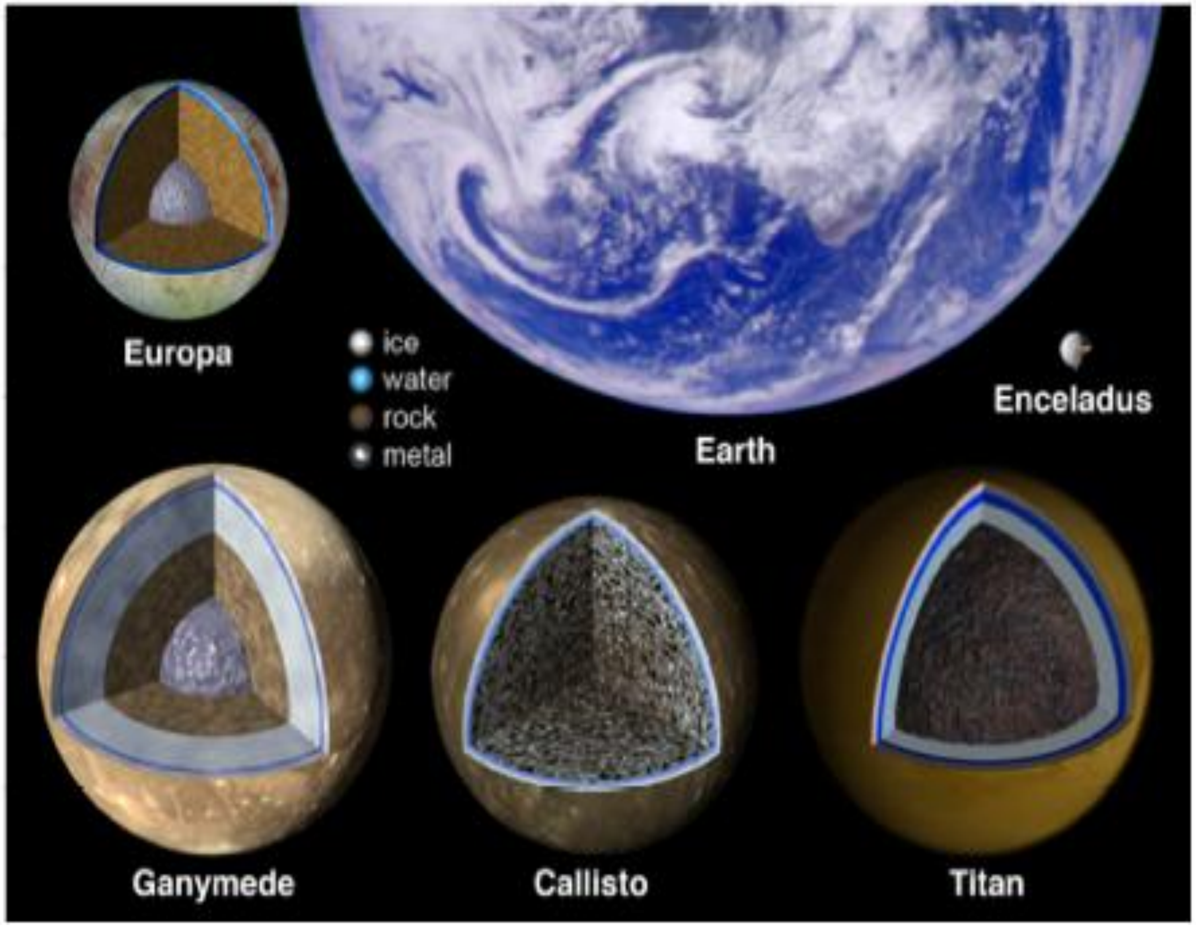
Science Goal



- **Basic Concept**
  - **Use passive RF receiver on Europa (or other outer planet ice moon) orbiter to observe RF signals from high energy neutrino interactions in ice crust**
  - **Use characteristics of observed events to determine thickness of ice layer**
- **Expected Advantages over ice penetrating radar:**
  - **Lower power, weight, volume**
  - **No need for large self-deploying antenna**
- **Enabling factors for neutrino detection:**
  - **Cold Europan ice may be very transparent to RF**
  - **Thick ice crust provides very large detector volume for high event rate**

Outer Planet Ice Moons

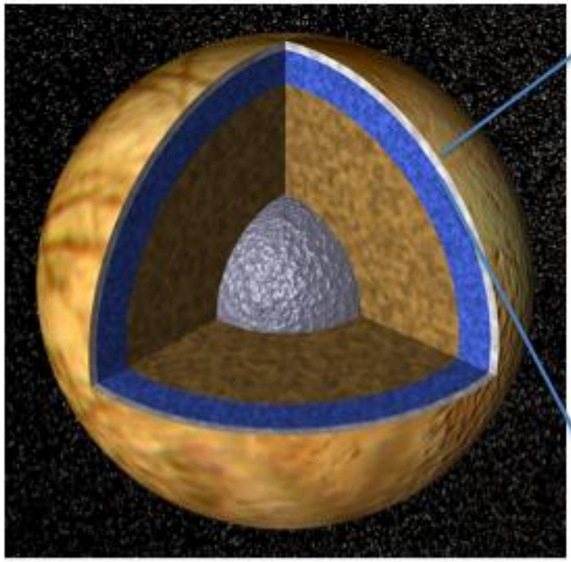
- **The "Ocean Worlds" - moons of Jupiter and Saturn that harbor oceans under an icy shell.**
- **Understanding the evolution and structure of these ice covered ocean moons yields important clues to how conditions hospitable for life can form in the universe.**
- [Figure taken from the NASA Jupiter Europa Mission Study Final Report]

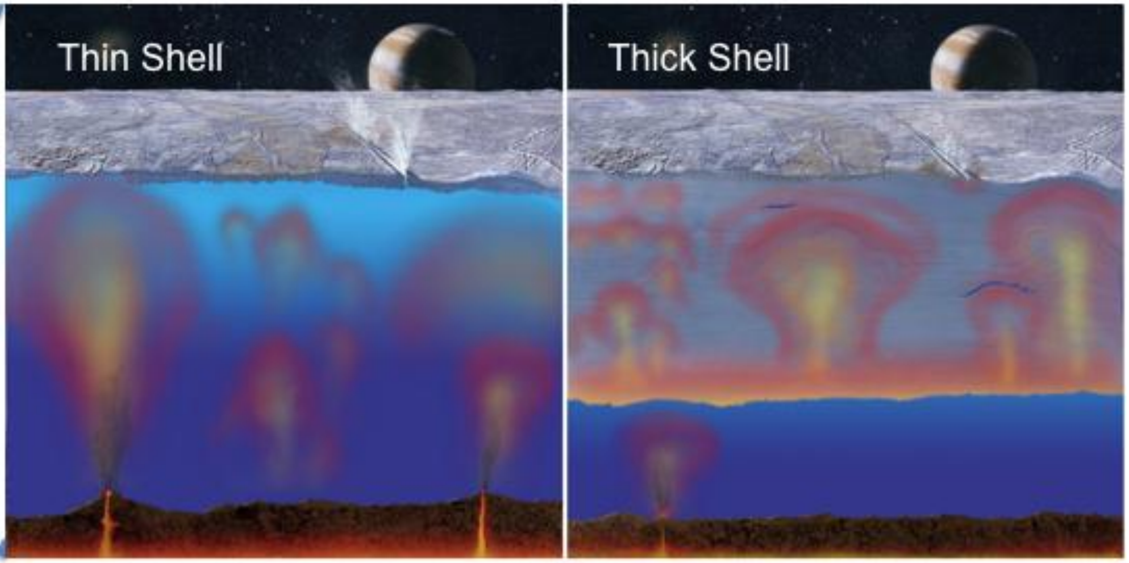


Planetary bodies shown to scale

Poster Child for PRIDE: Europa
Galilean Moon of Jupiter

- Smallest of the Galileans. (R=1560 km, a little smaller than Earth's Moon)
- Outer planet moons covered with ice: possibly 10s of km thick, covering watery oceans where life may exist
- Sensing ice depth on Outer Planet moons, especially Europa with an ancient underice ocean, is a high priority science goal





Europa is covered with a shell of ice whose thickness is unknown and is a source of speculation among planetary geologists. Shown above is a cutaway of Europa showing a shell of ice covering a deep ocean. To the right is an artists conception of thin and thick ice shell geologies on Europa. Tidal forces induce an unknown level of volcanism on Europa.

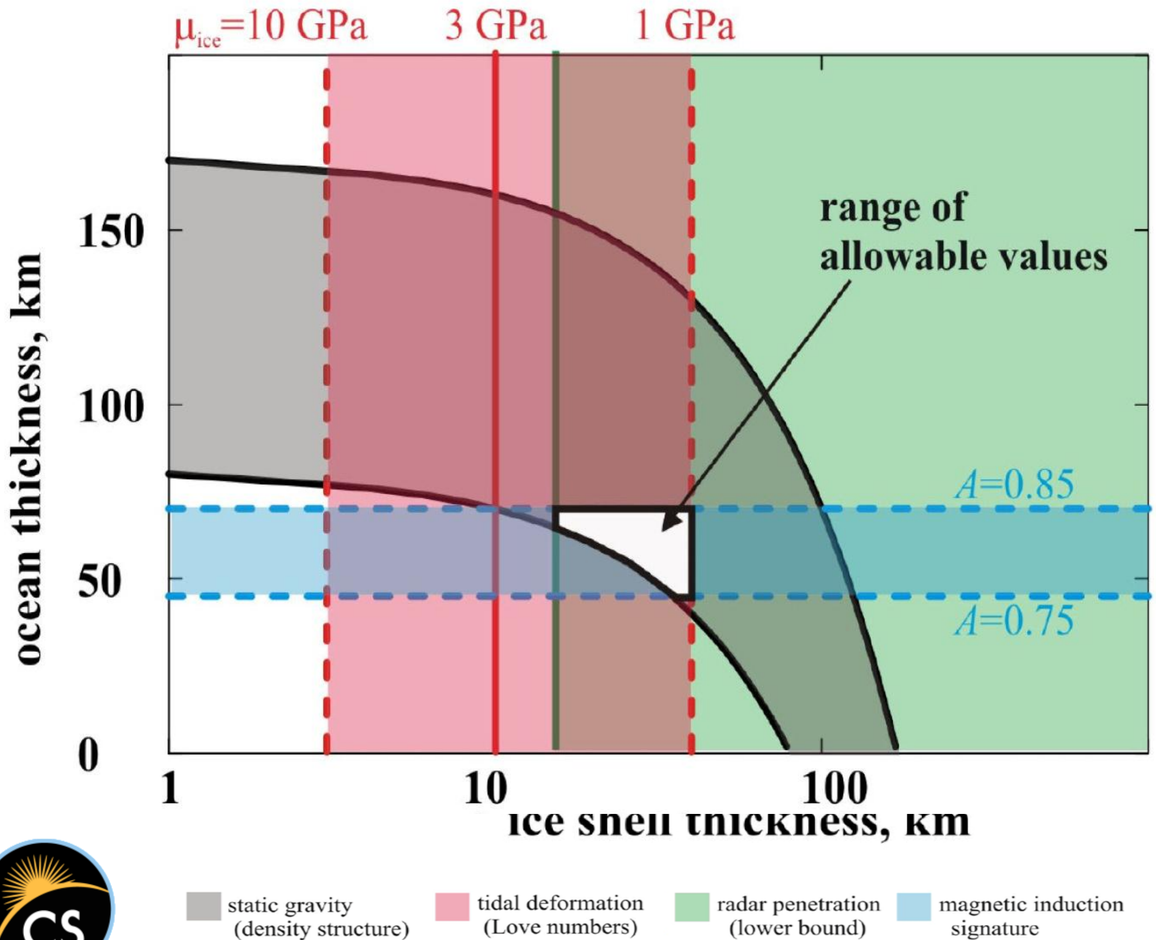
Ice Depth Measurements

- Methods of estimating thickness
  - Gravity measurements
  - Induced magnetization
  - Impact Craters
  - Surface Topography and Flexure model
  - Convective Tidal Dissipation
  - Ice Penetrating Radar Sounder

- All have drawbacks
  - Large uncertainty range
  - High power and complexity

Ice Depth Measurements

This particular (hypothetical) set of observations results in a range of acceptable ice shell thicknesses (15 to 40 km) and a range of acceptable ocean thicknesses (45-70 km). A different set of observations would result in different constraints, but the main point is that the combined constraints are more rigorous than could be achieved by any one technique alone. JEO will provide the measurements needed to constrain the thickness of Europa's ice shell.



- **Example using possible measurements from an ice penetrating radar, a magnetometer, and a laser altimeter on a proposed large planetary flagship mission (JEO) results in 15-40 km range**
- **Opportunity for improvement from novel measurements concepts**
- [Figure taken from the NASA Jupiter Europa Mission Study Final Report]

Instrument Table Summary

Comparison of Active Radar and Passive PRIDE Parameters

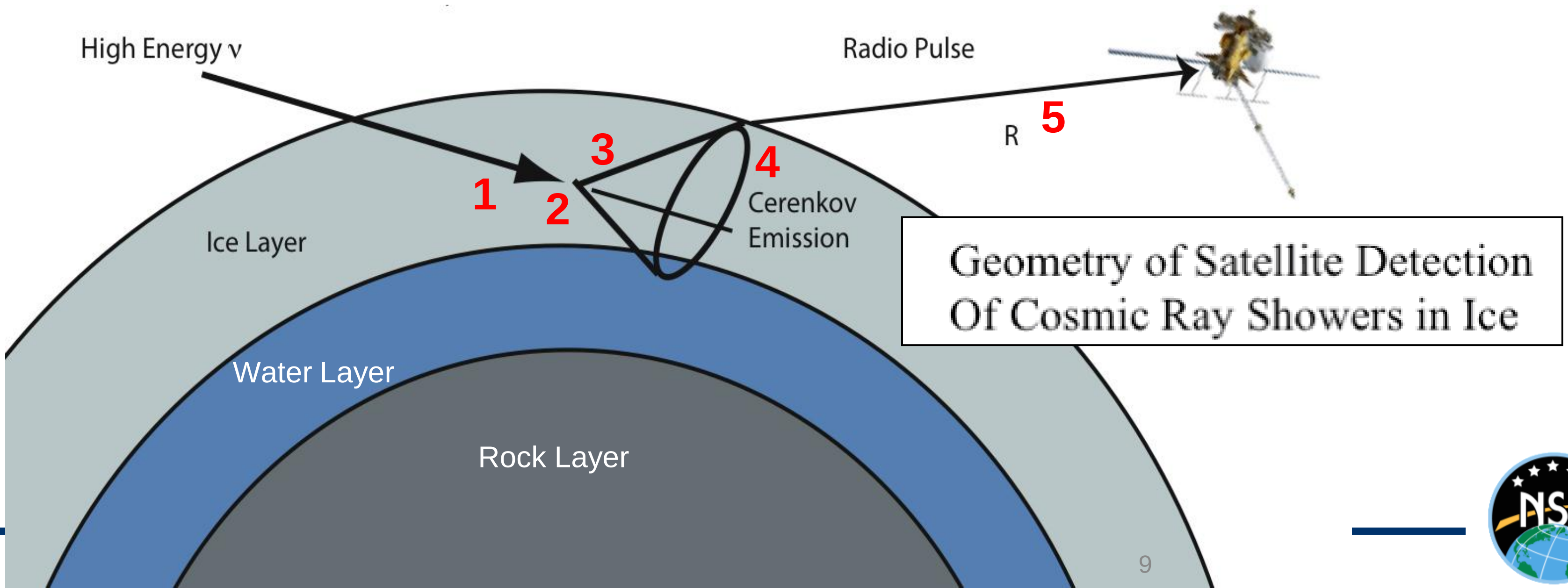
Parameter	Ice Penetrating Radar	PRIDE-JEO
Dimensions (m)	10 by 3 by 2 array	0.3 by 0.3 by 0.7 horn antennas (3 to 8) 0.25 by 0.25 by 0.25 (600 MHz tripoles)
Mass (kg)	~10	5-10 for horn antenna array (ROM), less for dipoles/tripoles
Power (W)	~1 average; 10^2 – 10^4 peak	O(10) (ROM)
Frequency (MHz)	5-50	200-2000
Passive/Active	Active	Passive
Notes	Must self-deploy from spacecraft at site	No moving parts. Antennas placed at open locations on SC body.

S/C Instruments cost ~$1M/kg implying PRIDE ~ $10M

Basic Concept

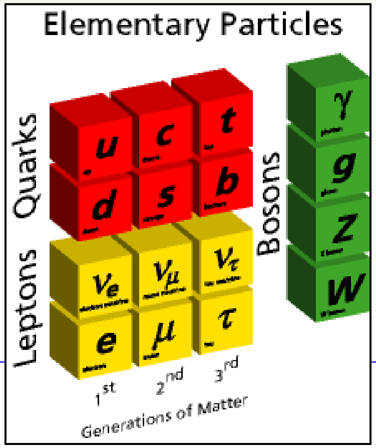
Use radio receiver technology to detect neutrino interactions in the ice

1. **EHE neutrinos penetrate through the ice sheet and interact within the ice to produce secondary charged high energy particles**
2. **Secondary particles go on to interact and produce additional particles, leading to a shower of charged particles moving through the ice for several meters**
3. **Shower of particles will develop a net negative charge due to electrons from the ice scattering into the shower**
4. **The shower moves faster than the speed of light within ice (c/n_{ice}), and produces Cerenkov radiation at wavelengths greater than its physical size (the Askaryan effect)**
5. **Emitted radiation peaks at ~0.2-2 GHz and is detected by an orbiting spacecraft**

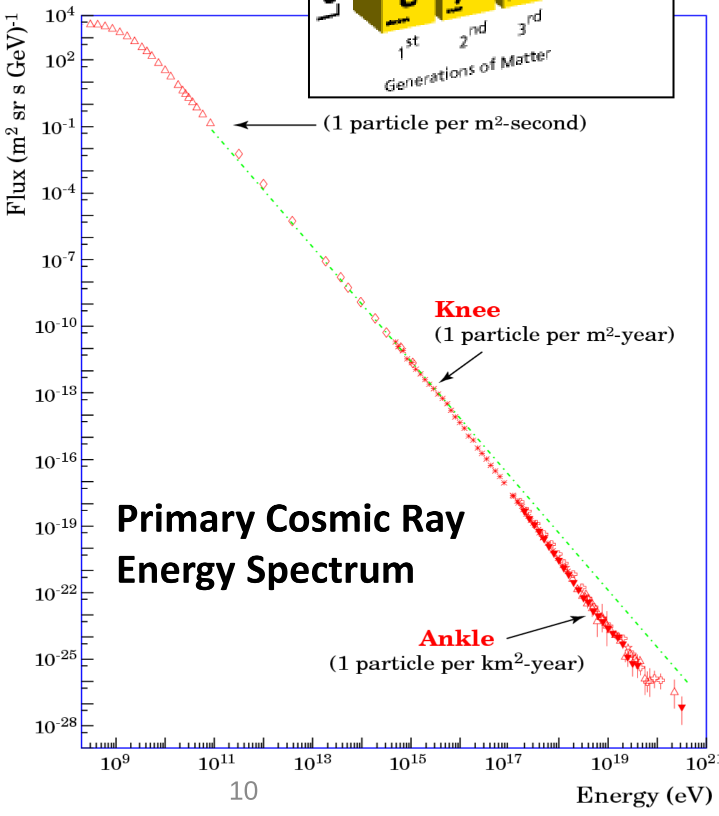


Astrophysical Neutrinos

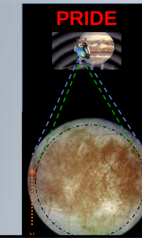
- Neutrinos: "... the most tiny quantity of reality ever imagined by a human being"
  - Very little mass, no charge
  - Only interact via the weak nuclear force
  - Tiny interaction cross section grows with energy so that the extremely high energy neutrinos neutrino's mean free path in ice ~ 700 km $(10^{19}\ eV/E)^{0.4}$



- Highest energy cosmic rays observed are protons with E > 10^{20} eV (50 J)
- Acceleration sites at highest energy are currently unknown
- Extreme High Energy (EHE) cosmic ray protons will interact with CMB photons to produce guaranteed source of EHE neutrinos
- There is some uncertainty in the absolute flux of EHE cosmic rays
- Additional sources may also exist, increasing fluxes
- By the time PRIDE could arrive at Europa (c. 2030?), two decades of observations should significantly reduce the uncertainty in the EHE neutrino flux



Questions

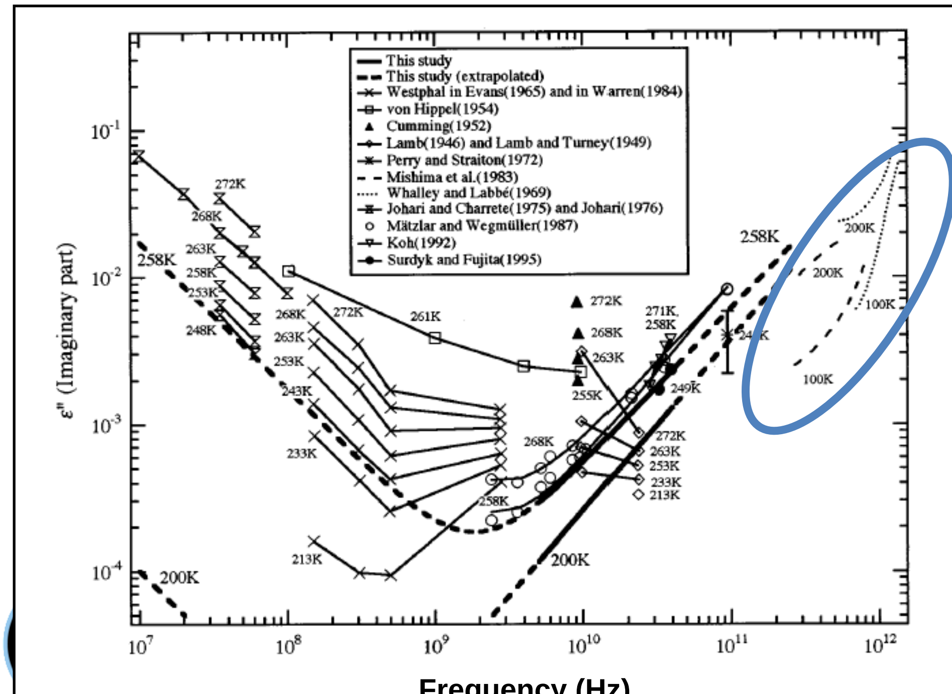


- Can this signal be exploited to sense the depth of the ice? (see also Shoji, et al., 2011).
- Are there problems with making an instrument that could perform these measurements on an Outer Planet mission?
  - Tough constraints on power, size, & mass
  - Backgrounds near Jupiter
- Initial PRIDE results presented at EJSM Instrument workshop, 2009
- Updated PRIDE results now in Icarus **220** (2012) 877.

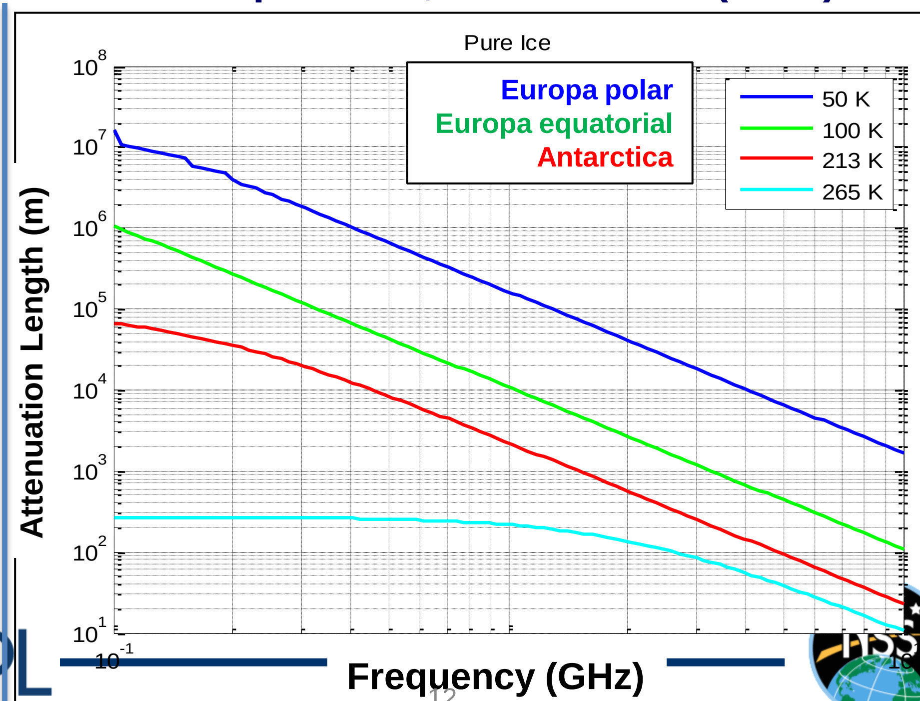
Pure Ice Transparency

- RF transparency of ice increases with decreasing temperature
- At Antarctic temperatures of -60C, L_{att} at several hundred MHz is ~6 km, allowing an RF sensor to observe pulses from the bottom of the 3 km ice cap
- At Europan temperatures, L_{att} is (maybe) many times longer (10 to 100 km at 100 K, 100's of km at 50 K for pure ice) making it possible to observe interactions to depths of tens of km, and thereby to probe the depth of the entire icy layer
- Note: ice impurities (like salts, rocks, water pockets, etc.) can make L_{att} much shorter!

Experimental Results



Model: Attenuation length of pure ice vs. freq. and temperature, from Mätzler (2006)



Europa Event Simulation

Monte Carlo simulation of the neutrino signal performed as a function of source spectrum, ice depth, satellite altitude, and detector characteristics

1. 10^5 simulated neutrinos were generated at random locations with random incident directions at energies of 10^{18}, 10^{19}, 10^{20}, and 10^{21} eV
2. Neutrinos were propagated through Europa along discrete 0.1-km steps until each either interacted or passed through Europa
3. For interactions, the path of the RF signal to the satellite was determined, assuming a smooth surface and an index of refraction of 1.8
4. For each event observed by the satellite, the signal-to-noise ratio (SNR) at the receiver was calculated
   - The detector was modeled as a single antenna of area 0.25 m^2, central frequency = 600 MHz, and bandwidth = 600 MHz.
   - Events were considered detected if they had an SNR ≥ 5
   - Satellite altitude was varied between 100 and 500 km
5. Characteristics of detected events, such as **event rate, SNR, and observation direction**, were collected for various combinations of ice depth and satellite altitude.

Simple Simulation Done to Determine Remote Signal

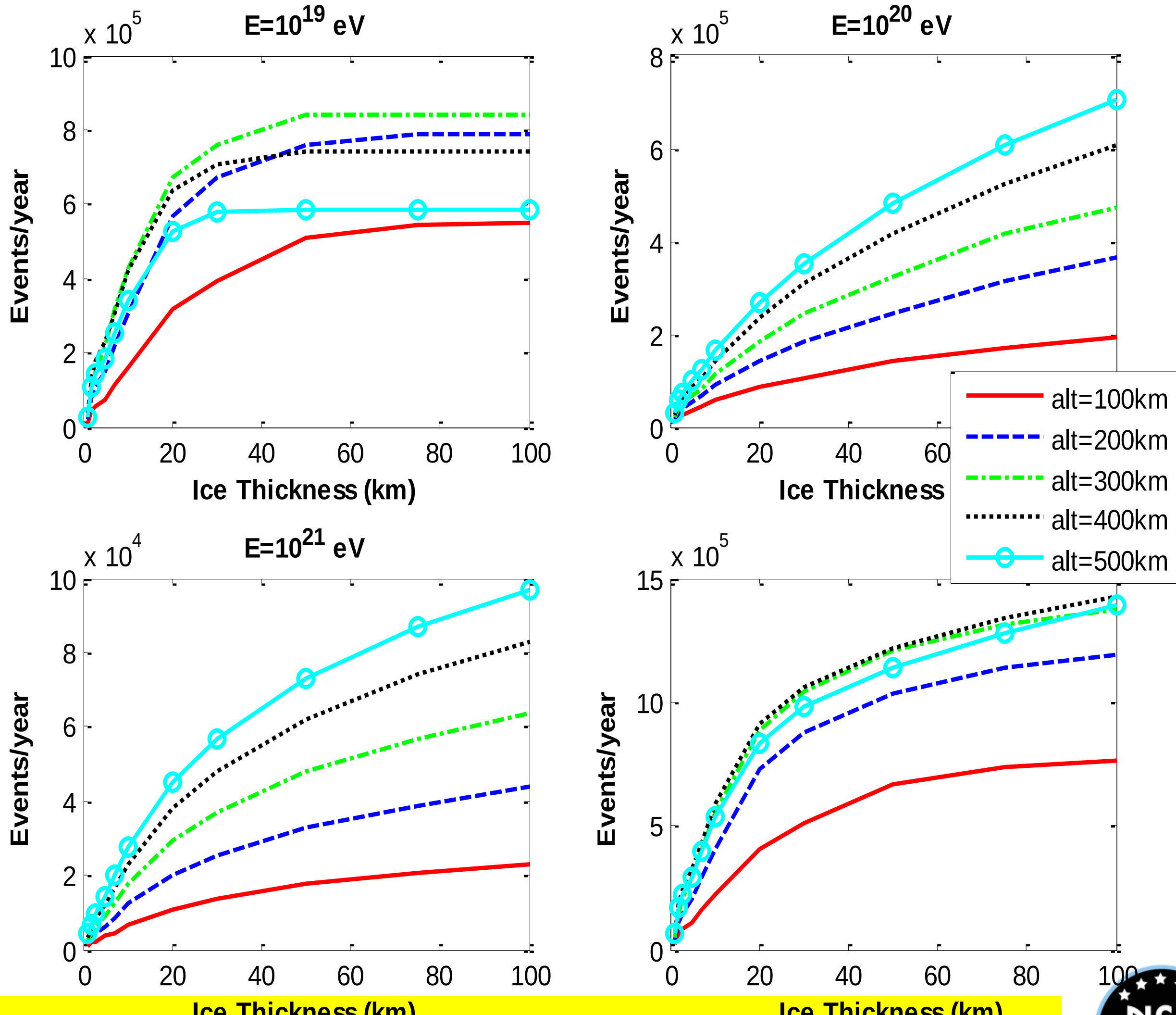
Signal to Noise

- Signal: Neutrino of energy E_n generates a cascade of energy $E_c = yE_n$, where $<y> = 0.22$ (empirical result)
- Cascade generates a number of secondary e-/e+: $N_{e+e-} \sim 10^9 (E_c/10^{18}$ eV).
- Excess of negative charge generated: $N_{ex} = 0.2 N_{e+e-}$
- Signal calculation for a 10^{19} eV primary initiated cascade:
  - For $n \sim 1.8$ at 600 MHz with a 600 MHz bandwidth, energy generated by average particle over 6 m track length: $W \sim 1.5 \times 10^{-25}$ J.
  - Sum of energy generated from all net negative charge: $W_{tot} = N_{ex}^2 w = 3 \times 10^{-8}$ J
  - Radiated into a Cerenkov cone at angle θ_c: $\cos(\theta_c) = 1/n\beta$, $\beta = v/c$
  - For parameters assumed: solid angle $\sim 2\pi \sin\theta c\, \Delta\theta c \sim 0.36$
  - Power per solid angle = $W_{tot}/(0.36$ sr$) = 8 \times 10^{-8}$ J sr^{-1} radiated
  - For 100 km orbit, the typical range for to the spacecraft is ~ 400 km, which yields a peak flux $F_{peak} = 6 \times 10^6$ Jy (Janskys: 1 Jy=10^{-26} W m^{-2} Hz^{-1})
- Energy radiated and signal depend on the <u>square</u> of the number of particles
- Thermal noise : Background due to thermal emission is roughly the thermal energy divided by the effective antenna area kT/A
  - Receivers will be staring at Europan ice at ~100K
  - For an effective area of about 0.25 m^2: kT/A ~ 5.5×10^5 Jy

SNR ~ $10^*(E_\nu/10^{19}$ eV$)^2$ for small (.25 m^2) antenna at 400 km

Detected Event Rate

- Events/year detected vs. ice sheet depth and neutrino energy
  - No events detected at 10^{18} eV
  - Lower Right = all energies, assuming an E^{-2} spectrum
- At extreme high energies, ice depths up to 100 km can be determined from event rate
- Maximum event rate at satellite altitude of about 300-400 km
- Briny ice case event rates (not shown) level off before ~20 km



Event rate is very sensitive to ice sheet thickness

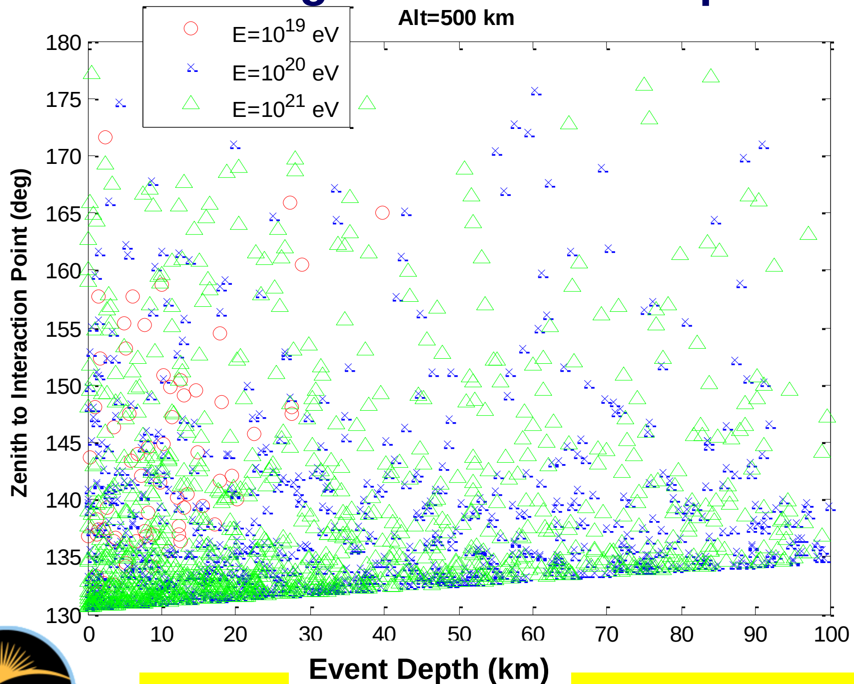
Source Event Rate

- Uncertainties in source flux make derivation of ice depth from detection rate alone uncertain
  - Primary source is cosmic ray protons interacting with intergalactic cosmic microwave background photons to produce EHE neutrinos (GZK effect)
  - Absolute flux of neutrinos depends on the density of cosmic background photons (well known) and the flux of EHE cosmic rays, known to better than a factor of 10 (Waxman-Bahcall upper limit is well known…)
  - Other potential sources of high energy neutrinos may evade the W-B GZK bound, e.g., optically thick active galactic nuclei, which could produce possibly one to two orders of magnitude more events
- Several experiments are underway to measure the charged cosmic ray and neutrino fluxes, and the absolute calibration will be better known in a few years
- By the time PRIDE arrives at Europa, one to two decades of observations should significantly reduce the uncertainty in the flux of neutrinos in the EHE range
- Nevertheless, additional observables that are dependent upon ice depth but independent of source neutrino flux are desirable

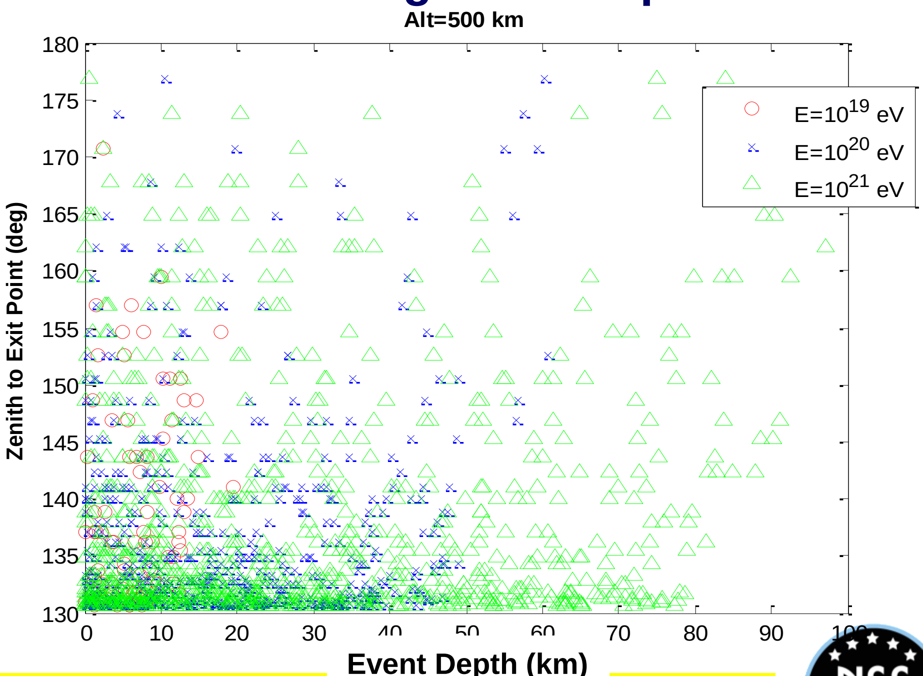
Zenith Angle Distribution

- Most events originate from a narrow angular range, but at greater depth minimum zenith angle to interaction point increases and events may not cluster as much near the minimum
- Most events arrive from a narrow annulus near the horizon due to refraction at the surface
  - At greater depths a higher fraction of events may arrive from larger zenith angles
  - In addition, surface roughness causes some energy to exit the ice with a lower refraction angle, making the real distribution somewhere between the two cases shown

Zenith angle to interaction point



Zenith angle to exit point



Zenith angle is potentially sensitive to ice sheet thickness

General Depth Measurement

Input Variables

- Neutrino Source Spectrum
- Ice Impurities vs. Depth
- Ice Temperature vs. Depth
- Ice Non-Uniformities
- Surface Roughness
- Backgrounds
- Ice Shell Thickness

Complicated convolution…

Observables

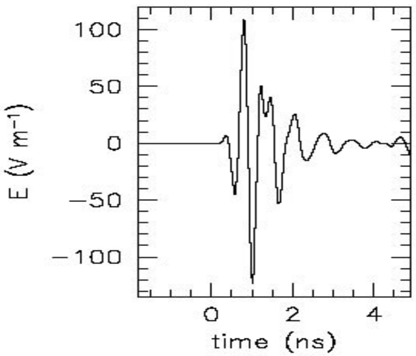
- Event Rate
- Arrival Direction
- Intensity
- Frequency Content
- Direct-Reflected Δt
- Polarization
- Phase?
- Cerenkov Cone?

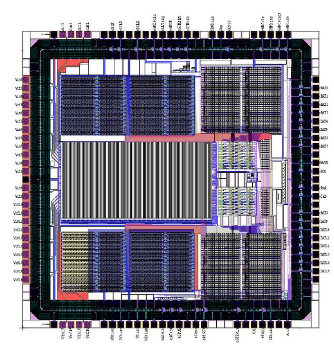
Complicated deconvolution/inverse…

Variety of measurements can be combined to (hopefully) disentangle ice thickness from other effects

Instrument Parameters

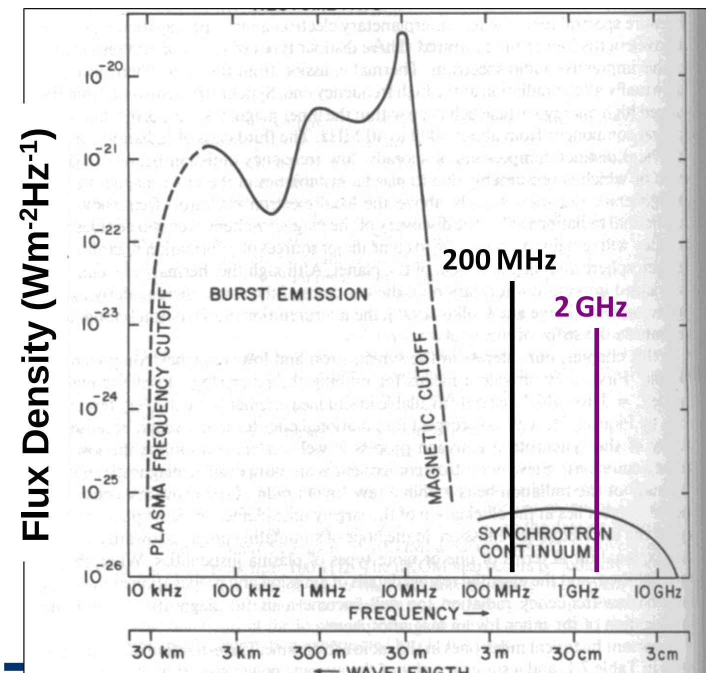
- Backgrounds: 0.2-2.0 GHz is the sweet spot between Jupiter's thermal noise and radio burst emission
- Radio antennas could be tripoles or wide horns (to maximize planetary disk view).
- Power frugal triggering and digitization schemes possible
- Data volume is easily within outer planetary mission constraints

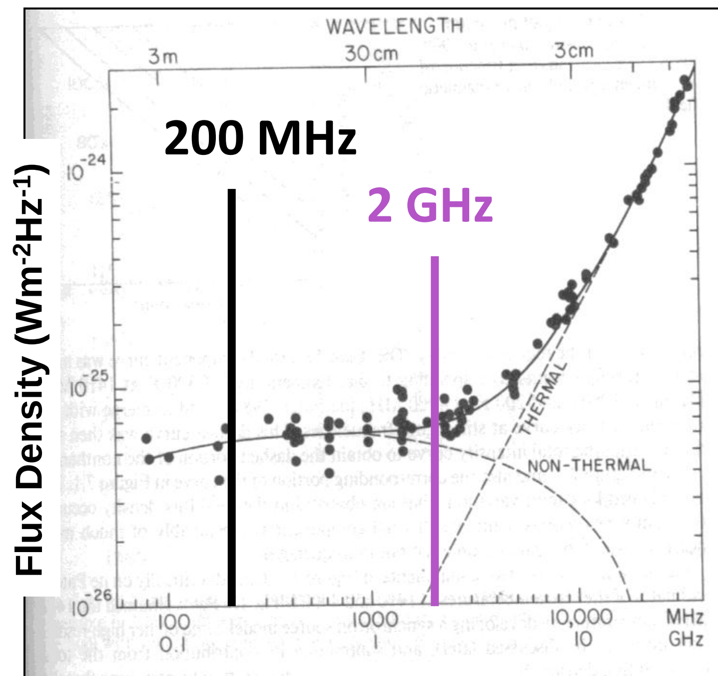




Background: Local RF Environment

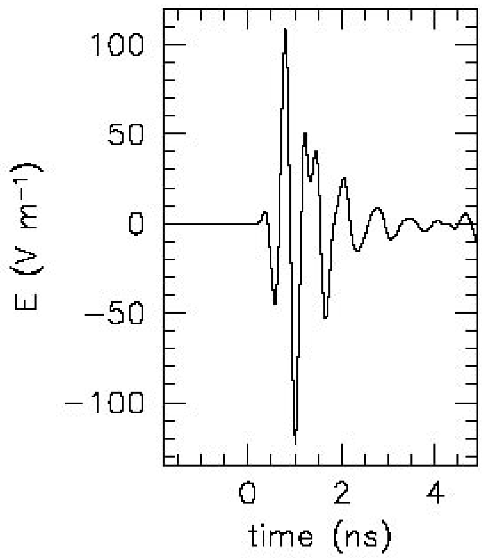
- 10’s of MHz or less: considerable burst emission
- > a few GHz: thermal emission from Jupiter
- ~100 MHz to a few GHz: synchotron emission from e’s in Jupiter’s magnetosphere
- 3rd source is much less than the first two, and matches the 0.2-2GHz range that is optimal for both cerenkov emission and ice transparency
  - Peak = 5e6 Jy at Europa = Comparable to signal at 10^{19} eV
  - Directional: can be considerably reduced because it will be from off-axis

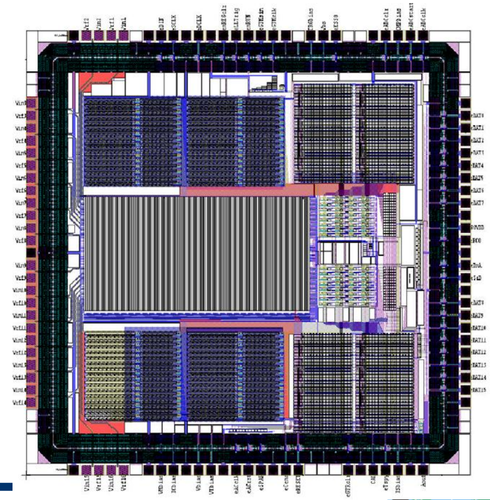




Fast Digitization

- Significant signal power at large frequencies (1-2 GHz)
- Digitization at ~1-3 GHz needed
- No commercial solution: too much power (order of 10 W/channel for commercial ADC's)
- Potential solution: Switched Capacitor Arrays (SCA)
    - Used on ANITA, other high energy physics and cosmic ray physics experiments requiring high digitization rates and low power
    - Charge is stored analog in array of capacitors while trigger is formed
    - Array of capacitors is read out by ~MHz ADC if event trigger occurs
    - Low event rate = low dead time even for slow readout
    - Power ~20 mW per channel
- Issues: rad-hardness, survivability still to be investigated

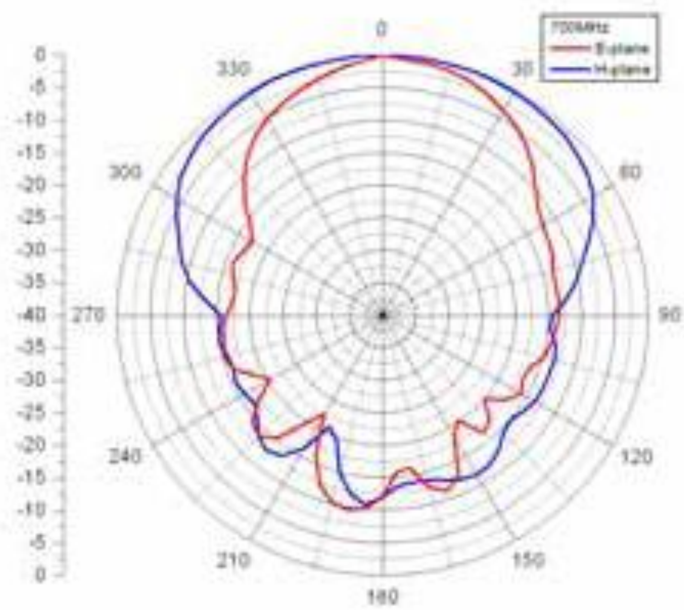




Low power fast digitization solutions exist

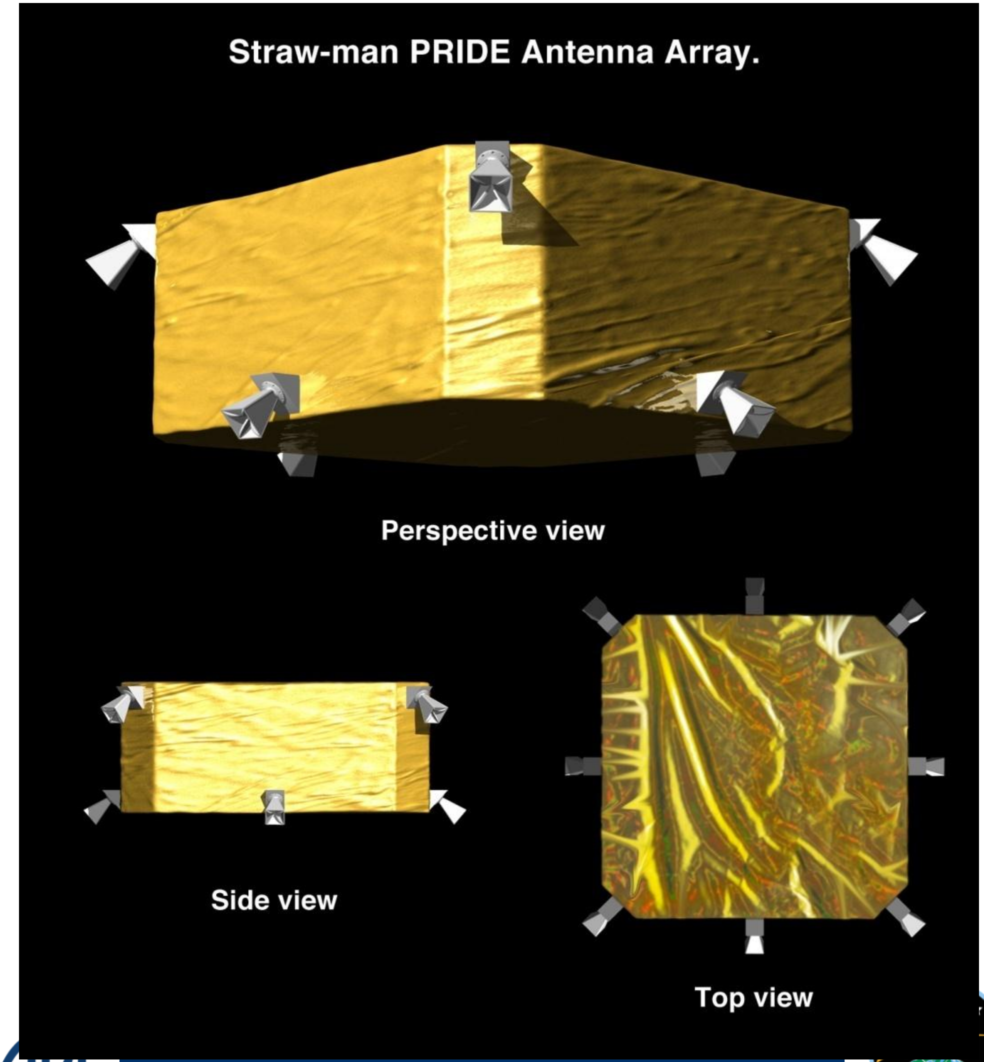
Antenna Design

- Wide bandwidth used in the signal calculation can be achieved with a ridged horn antenna
- Starting point = commercial dual-polarized 700 MHz-6 GHz horn
  - 700 MHz - 6 GHz Frequency Range
  - Measurements for Both Horizontal and Vertical Polarization
  - Cross Polarization Isolation Better Than 20 dB
  - Size = 35 by 23 by 23 cm, mass = 5 kg
  - Made for high power transmission
- Modifications:
  - Shorten to increase acceptance angle and decease weight
  - Reshape opening to ellipse so acceptance is greater horizontally than vertically
  - Lighten considerably for receive-only application
  - Expected final form factor (very rough):
    - 35 cm long by 72 cm high by 8 cm wide
    - Mass ~1-2 kg



Strawman PRIDE antenna array

- Need to cover annular solid angle about 10-20 deg wide, centered ~10-15 deg below horizon, for 360 deg around
- Minimum array = two antennas at different heights to allow zenith angle (but not azimuth) reconstruction
  - Additional antennas would enable improved angular reconstruction and sensitivity.
- Possible approach: two rings of 4 antennas at top and bottom of spacecraft, about 2-3 m apart
  - For acceptance close to 180 degrees in azimuth, each event will be observed by at least three antennas, with at least one on each ring, allowing both zenith and azimuth reconstruction
  - 0.15 to 0.3 ns timing accuracy ~ 2 deg zenith resolution

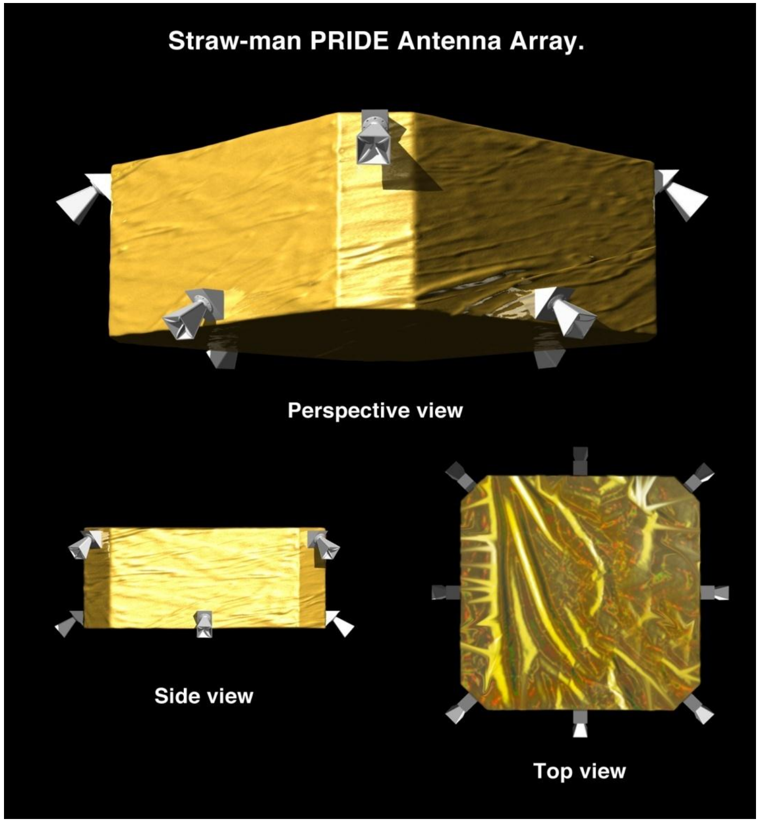


Next Steps

- Submit proposal to NASA PICASSO (Planetary Instrument Concepts for the Advancement of Solar System Observations) Program
  - Advance TRL from ~2 to 4 over 3 years
- Major proposal features
  - Adapt existing Askaryan Monte Carlo Simulation to PRIDE. Analyze risks/measurables from effects not modeled so far.
    - Higher fidelity simulation (neutrino propagation, antenna/receiver simulation, waveform simulation, etc) and greater number of events: greater accuracy
    - Model ice impurities and temperature models: could limit absorption lengths
    - Surface roughness: could reduce signal
    - Detect both direct pulse and reflected pulse from water-ice interface
    - Multi-antenna triggering, off-axis sensitivity, array optimization
    - Uncertainties in neutrino source spectrum
    - Backgrounds: cosmic rays, thermal from ice, burst and thermal from Jupiter, Galactic RF emission, and Solar burst emission
  - Enlist help to develop prototype hardware channel
    - Develop specialized digitization approaches (UCI)
      - Investigate SCA power requirements, radiation hardness, possible alternatives
    - Develop and test optimized antenna prototype (APL/UCI)

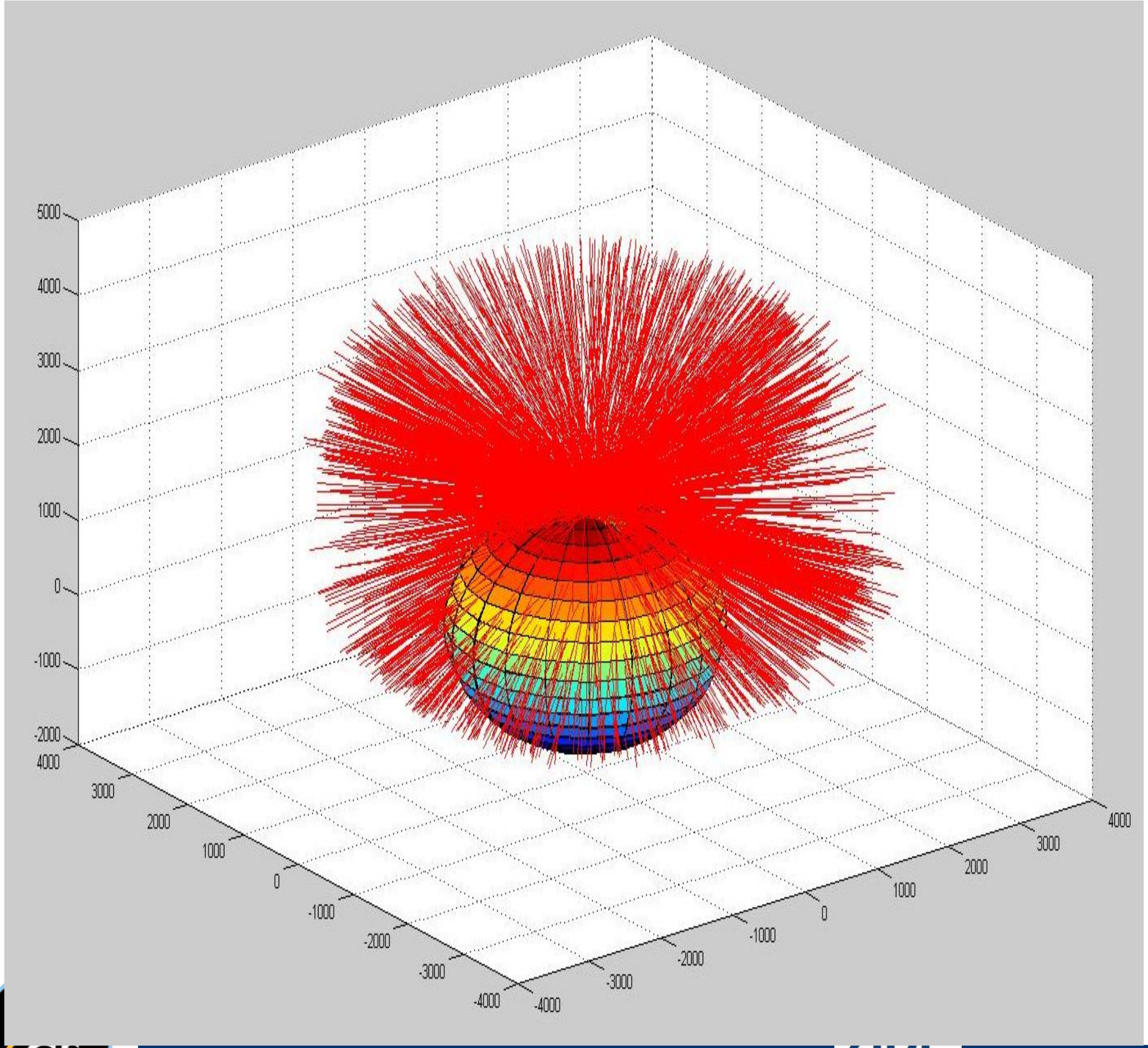
Conclusions

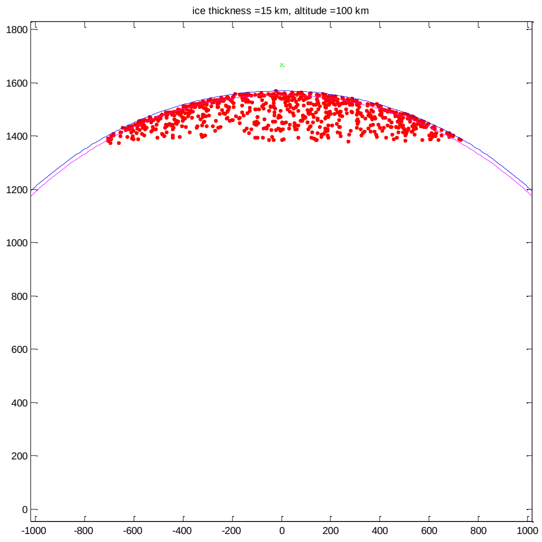
- **PRIDE began as an seemingly unlikely concept, but at this time it appears that it may be feasible**
- **Calculations show that there should be a strong detectable signal and that it can be used to resolve ice shell depth**
- **We have made a rough instrument design and demonstrated compatibility with an outer planet mission and looked at issues like**
  - **the local RF environment**
  - **signal digitization**
  - **antenna design**
- **However, many challenges still remain in the design**
  - **need a higher fidelity simulation with more realistic Europan Ice environment (ice discontuities, impurities, temperature gradients)**
  - **Need to develop electronics, optimize observing strategy to advance instrument design**
- **PRIDE's utility could be applicable to several ice moons: Europa, Ganymede, Callisto, and Enceladus (Titan?)**

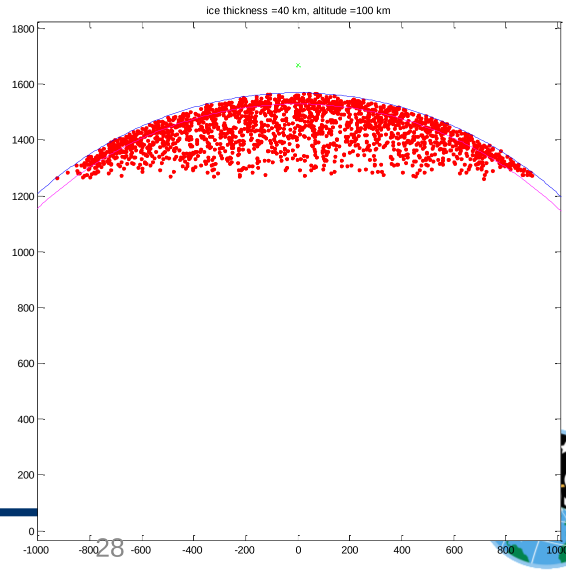


BACKUPS

Simulation Results







Risks
(What could go wrong, right?)

Risk Number	Risk Title	Explanation	Likelihood	Consequence	Mitigation Approach
1a	Ice Impurities, Major	Impurity level in ice reduces attenuation length so much that no meaningful depth mesurement is possible.	3	5	Research impurity measurements. Model effects in simulation.
1b	Ice Impurities, Minor	Impurity level in ice reduces attenuation length to set limit on greatest possible useful depth measurement.	4	3	Research impurity measurements. Model effects in simulation.
2	SCA devices use too much power	Fast digitization with SCA's not possible due to power requirements.	2	3	Develop new SCA devices for PRIDE application.
3	SCA devices not radiation hard	SCA devices cannot be made radiation hard.	3	3	Develop new SCA devices for PRIDE application.
4	No backup found for SCA's	SCA devices fail requirements due to 2 or 3 and no backup can be found to replace them.	2	5	Research alternative digitization approaches.

Risks
(What could go wrong, right?)

Risk Number	Risk Title	Explanation	Likelihood	Consequence	Mitigation Approach
5a	Background: RF Burst Emission	RF burst emission is too severe in Jovian environment, making false alarm rate too high	2	5	Research burst emission characteristics, model in simulation, develop triggering strategies.
5b	Background: Jovian Thermal / Continuous Emission	RF thermal/continuous emission is too severe in Jovian environment, making background or false alarm rate too high	2	4	Research continuous emission characteristics, model in simulation, develop triggering strategies.
5c	Background: Ice Thermal Emission	Ice thermal emission is too great, making background or false alarm rate too high	2	4	Research ice characteristics, model in simulation, develop triggering strategies.
5d	Background: Galactic RF Emission	Galactic RF emission is too great, making background or false alarm rate too high	1	4	Research galactic emission characteristics, model in simulation, develop triggering strategies.
5e	Background: Solar RF Bursts	Solar RF burst emission is too severe, making false alarm rate too high	1	4	Research solar burst characteristics, model in simulation, develop triggering strategies.
5f	Background: Nucleonic Cosmic Rays	Number of cosmic ray events is greater than number of neutrino events and the cannot be distinguished, making neutrino rate measurement impossible	4	5	Research cosmic ray events characteristics and rates, model in simulation, develop triggering strategies.

Risks
(What could go wrong, right?)

Risk Number	Risk Title	Explanation	Likelihood	Consequence	Mitigation Approach
6	Antenna mass too high	Antennas cannot be made low mass enough, violating spacecraft mass requirements.	2	5	Research and test array designs. Model array response in simulation.
7	Antenna number / array size	Number of antennas needed too great, violating spacecraft size and/or location ("real estate")requirements.	3	5	Research and test antenna designs. Model antenna response in simulation.
8	Uncertainty in neutrino spectrum	Poor characterization of neutrino source spectrum makes it impossible to infer ice depth from neutrino event detections.	3	4	Research EHE neutrino source models and expected measurements in next two decades. Model neutrino source spectrum models and uncertainties in simulation.
9	Surface Roughness	Rough surface could spread RF Cereknove radiation into wider solid angle, decreasing signal level	3	3	Research ice moon surface roughnesses. Model effects in simulation.

Risks

(What could go wrong, right?)

Likelihood

5					
4			1b		5f
3			3,9	8	1a,7
2			2	5b,5c	4,5a,6
1		10		5d,5e	
	1	2	3	4	5

Consequence

Comparison of Ice Attenuation Lengths

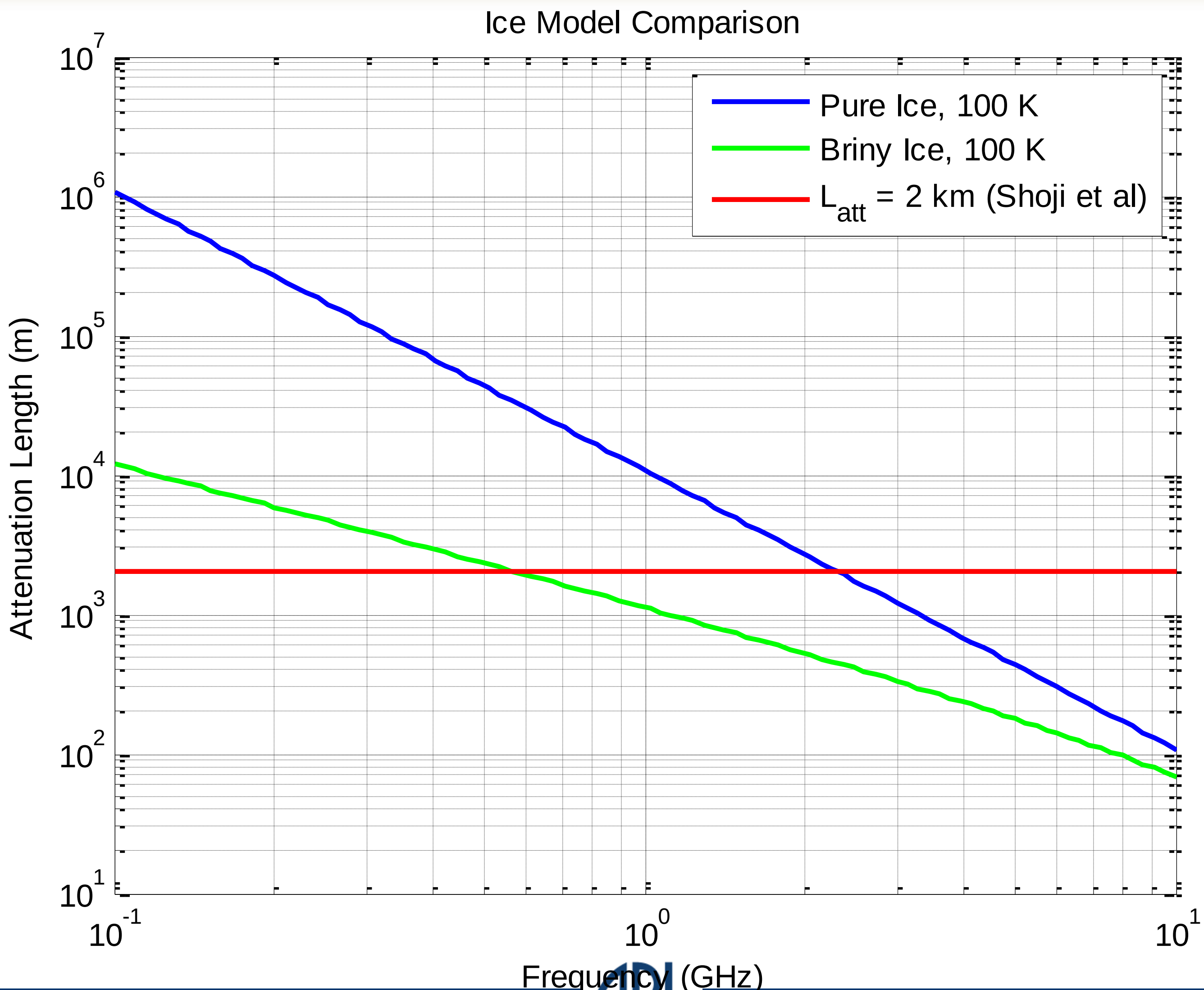


Figure 4. PRIDE (Passive Radio [frequency] Ice Depth Experiment). T. C. Miller

Pure Ice attenuation
SNR=5

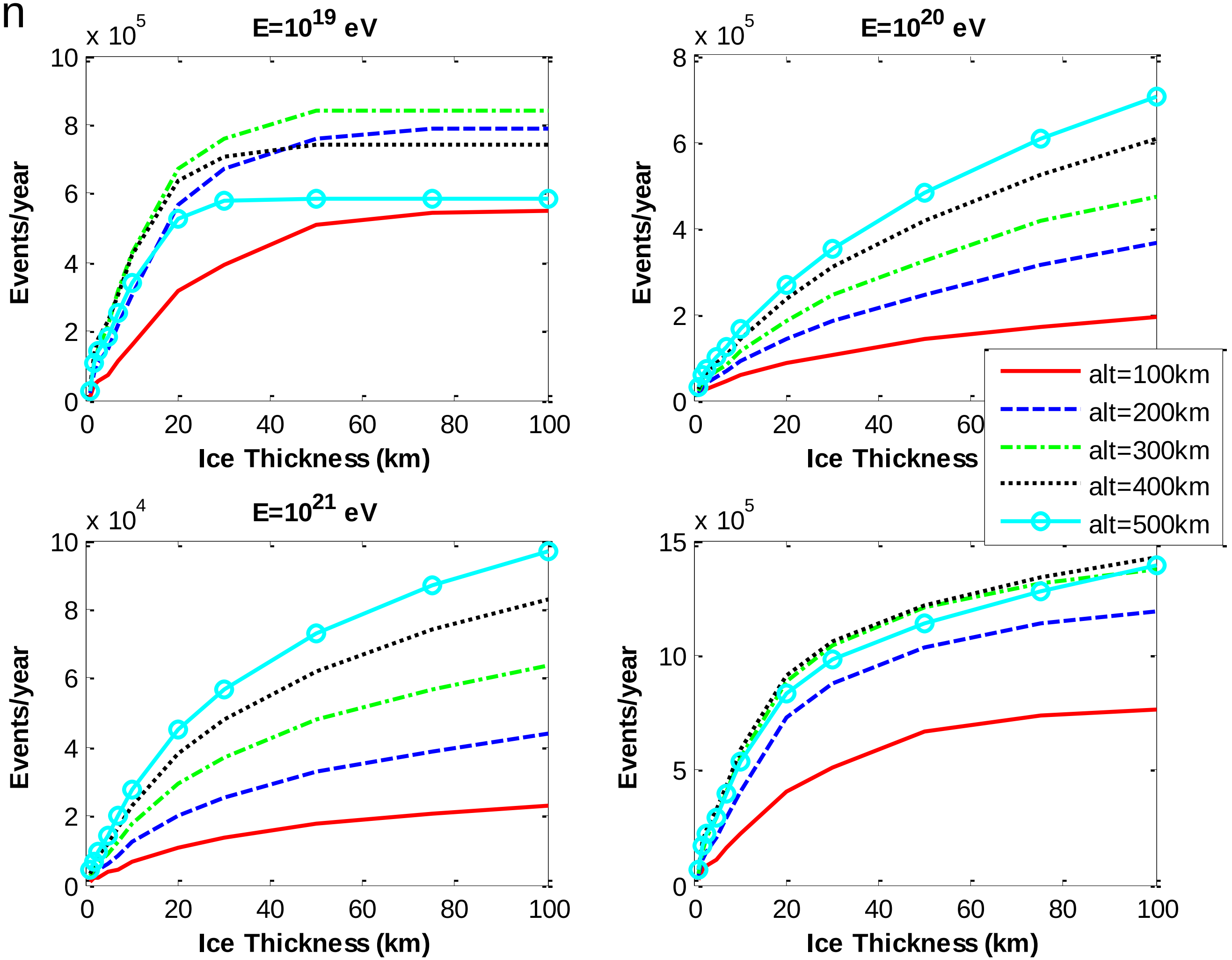


Figure 4. PRIDE (Passive Radio [frequency] Ice Depth Experiment). T. C. Miller

Brine attenuation
SNR=5

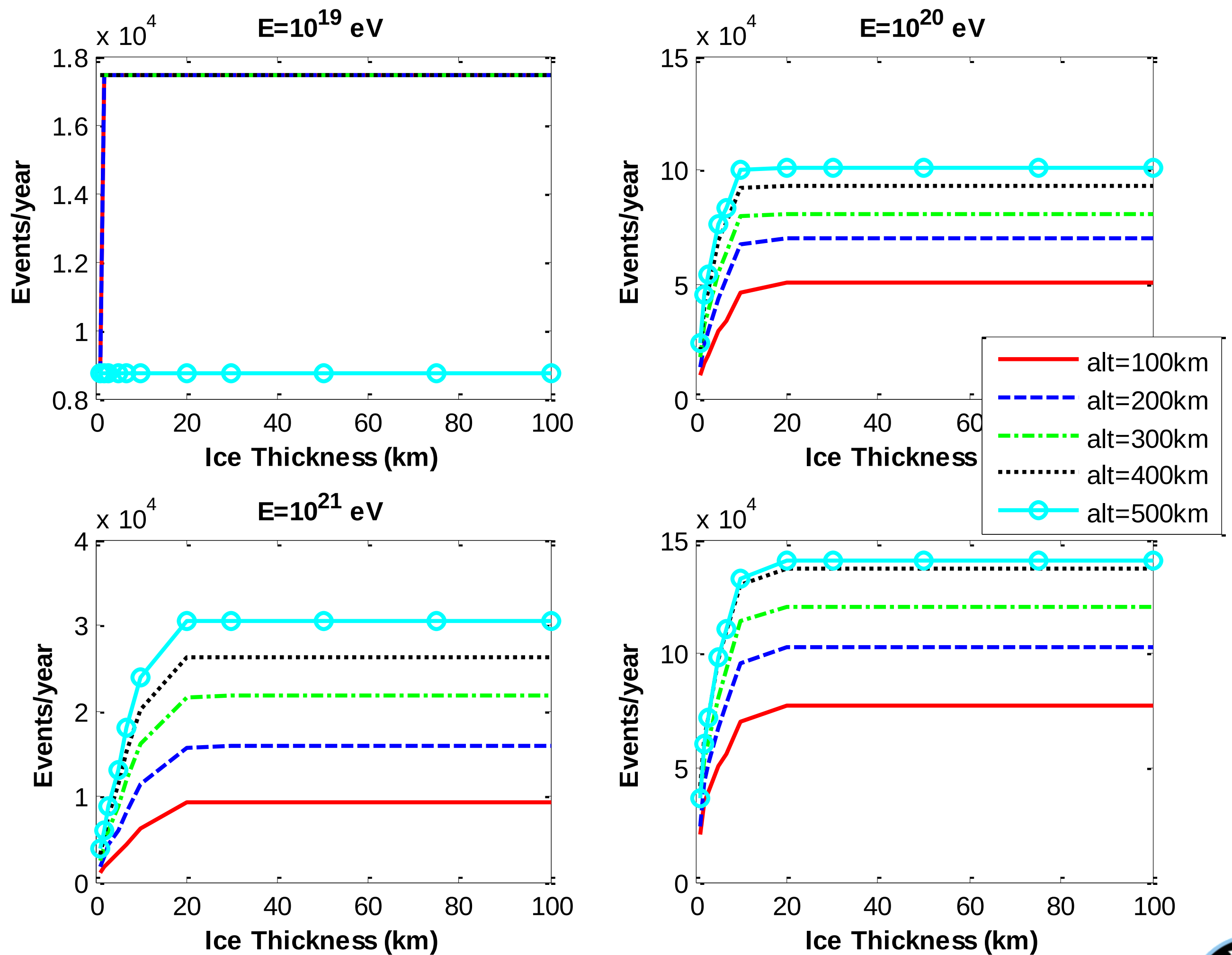
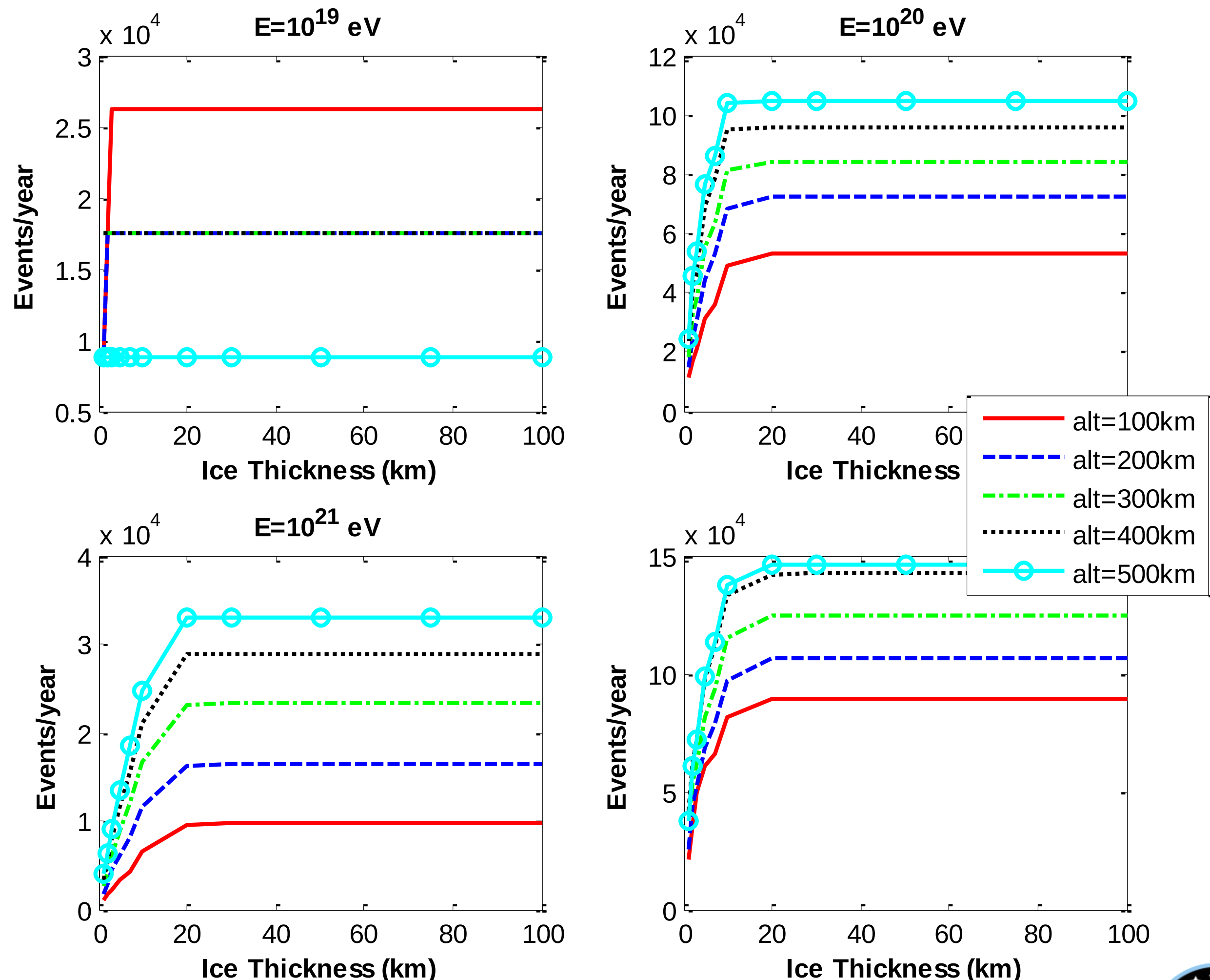


Figure 4. PRIDE (Passive Radio [frequency] Ice Depth Experiment). T. C. Miller

PRIDE

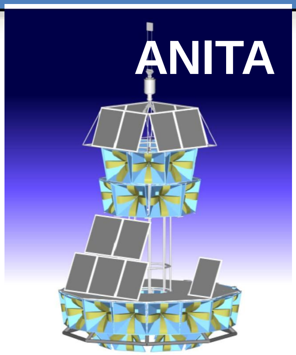
Shoji et al attenuation
SNR=5

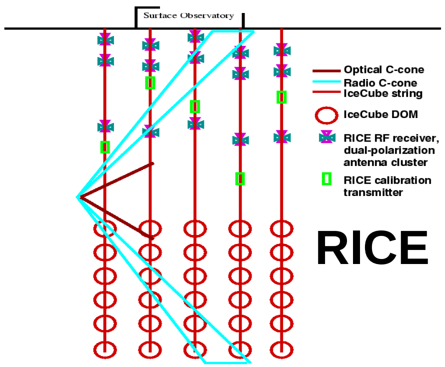


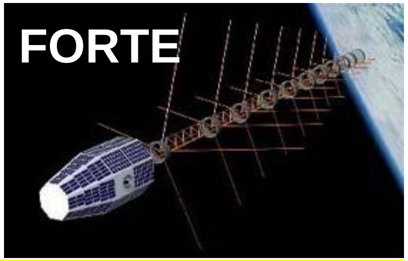
APL

Similar Projects

- Several existing projects have made use of the same RF detection mechanism to search for astrophysical neutrinos
- A variety of platforms and antenna types have been used
  - Accelerator demonstrations of Askaryan Effect
    - *D. Saltzberg et al., Phys. Rev. Lett.* 86 (2001): 2802-2805
  - ANITA = Antarctic balloon borne, horn antenna array
  - RICE = underice, fat dipole antenna array
  - FORTE = earth orbiting satellite
  - Lunar Orbiter = simulated lunar orbit, beam shaping or isotropic “tripole” antennas
  - ARIANNA – underice, like RICE, only much bigger







Projects using same phenomenon exist, are based on a variety of platforms, and use various antenna form factors

Future Simulations

- Multiple improvements can be made:
  - Greater number of events
  - Ice impurities
  - Surface roughness
  - Detect both direct pulse and reflected pulse from water-ice interface to measure thickness more directly on single events
  - Multi-antenna triggering, off-axis sensitivity, array optimization
- Another potential measurement that we have not yet analyzed but which could indicate depth is the frequency content of the detected pulses.
  - Attenuation lengths are shorter at higher frequencies, implying that events from greater depths will have less high frequency content than events from shallow depths
  - Our current simulation does not include pulse shape details, but this will be studied in the future

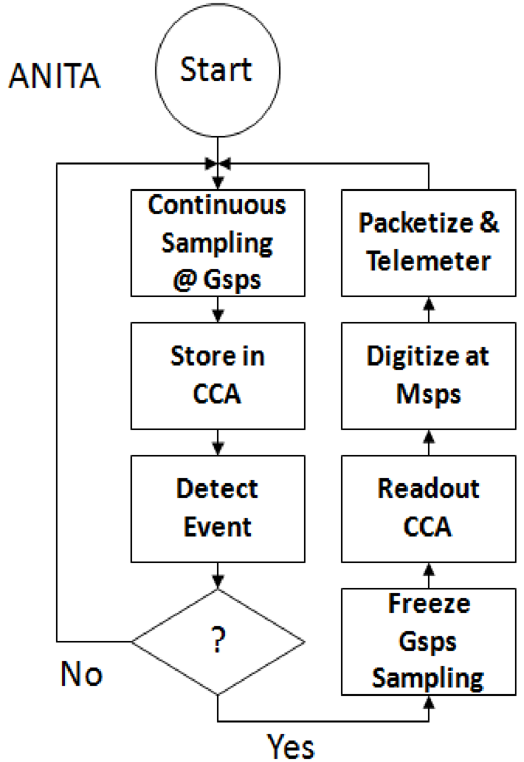
Better simulations needed to define and optimize observation strategy

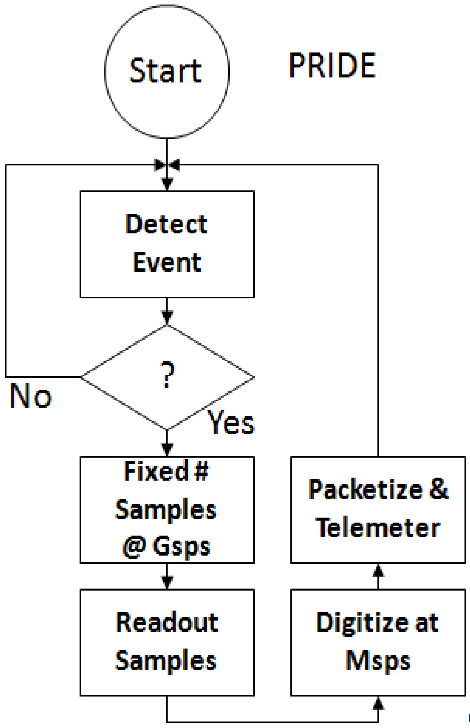
Challenges

- The power required for signal digitization and the feasibility of using the SCA approach need to be investigated in more detail, including such issues as radiation hardness and survivability.
- A higher fidelity simulation is required to conduct trade studies to perform more detailed design.
  - Necessary improvements include the effects of ice impurities, surface coatings, surface roughness, and unknown ice temperatures (and thereby attenuation length) vs. depth.
  - In addition, the antenna array needs to be simulated in greater detail, including galactic noise, multi-channel triggering, and event reconstruction capability.
- Antenna size, mass, and number required to measure ice depth, rather than simply to achieve the greatest possible capability, must be investigated in greater detail.

Digitization: Flow Chart Comparison with ANITA

- In order to further reduce the risk of exceeding power capabilities, we propose to also investigate modifications to the SCA triggering approach as shown
- Signals to the SCA ring would be routed through on-chip analog delay lines and the SCA memory written to only if an initial simple trigger is formed, reducing duty cycle and power consumption



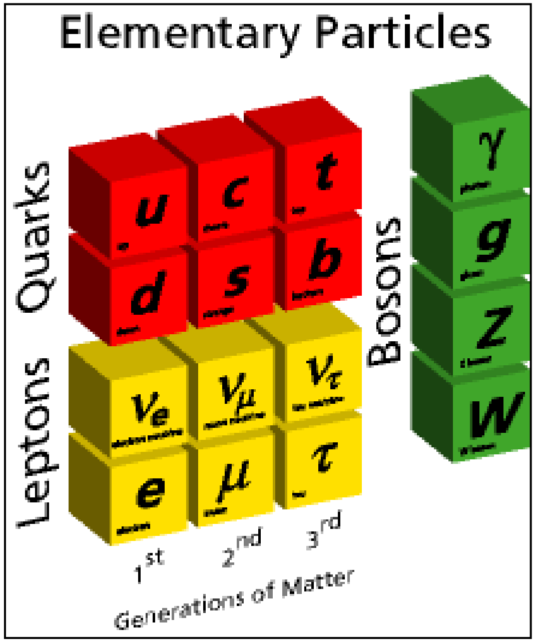


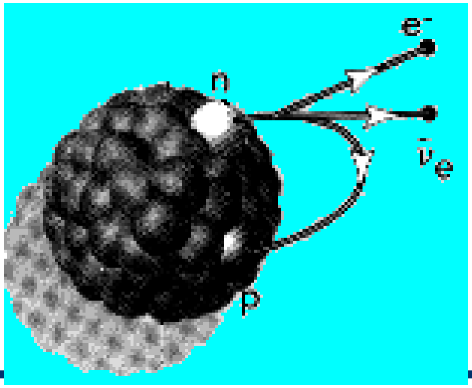
Data Volume

- Number of signal events is very low from data volume viewpoint = order of 1000/year
- Prime determinant of data volume is the noise trigger rate, which can be adjusted by adjusting threshold and triggering requirements
- Rough date volume calculation
  - Noise ~ 1 event every few minutes
  - Signal ~1000 events/year
  - Event size = 16 channels × 128 samples × 10 to 12 bits
  - Noise ~ 20,000 bits/100 seconds ~ 200 bits/second
  - Signal ~ 10/day ~ 0.3/hour ~ 3 bits/second
- Telemetry can be reduced further with initial onboard software trigger to reduce rate to anywhere between noise and signal
  - small amount of raw data can also be sent each day for calibration and monitoring.
  - This type of architecture is used by remote neutrino experiments such as AMANDA and Icecube.
  - Also note that ANITA, which obtains similar data, has achieved compression ratios of 3 to 5 using lossless compression schemes, which can further reduce telemetry requirements

Neutrinos

- "... the most tiny quantity of reality ever imagined by a human being"
  - Very little mass
  - No charge
  - Only interact via the weak nuclear force
  - An average neutrino will go all the way through the earth without ever interacting...
- Added to particle theory by W. Pauli in 1930 to preserve conservation of energy in beta decay

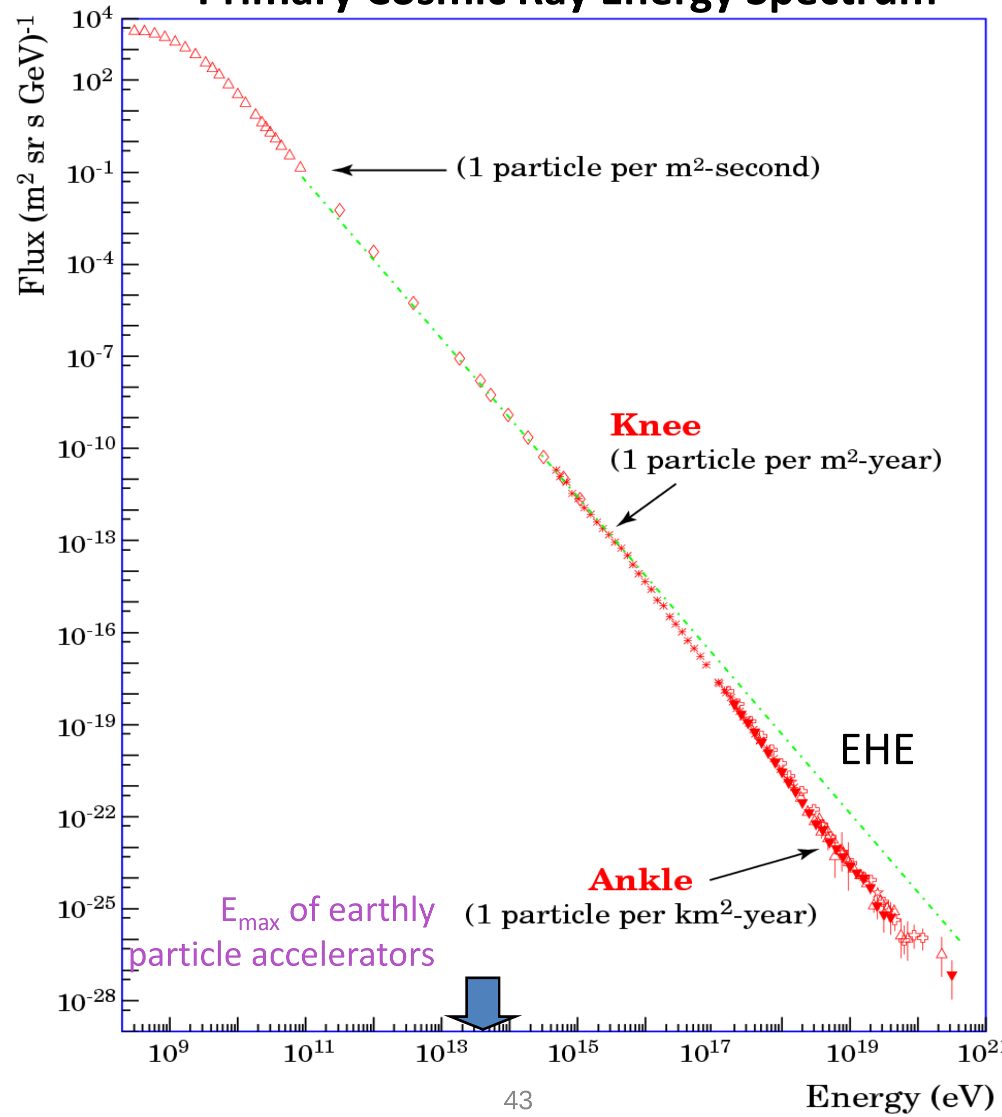




Source of Neutrino Events: EHE Cosmic Rays

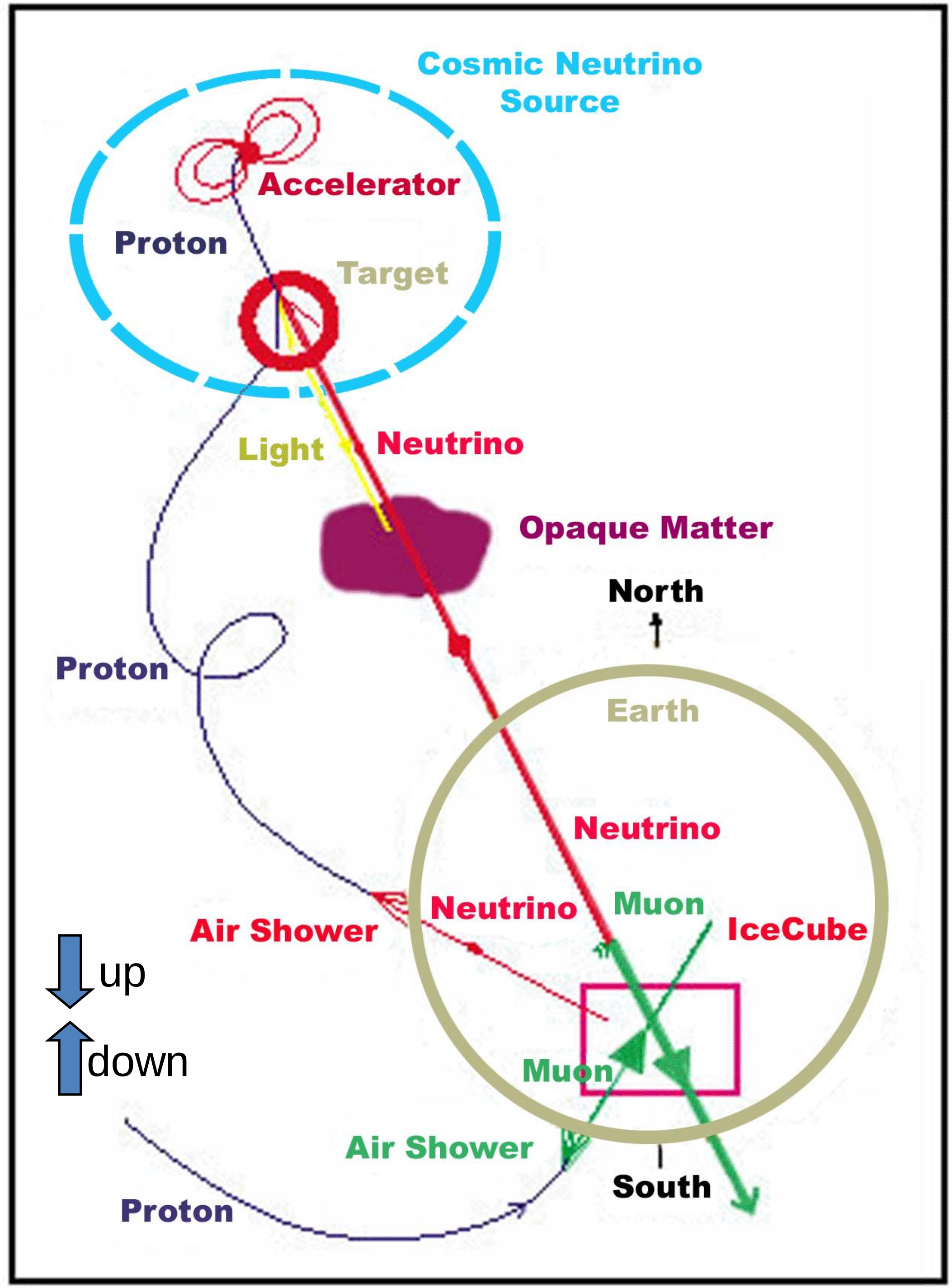
- Highest energies observed are protons with E > 10^{20} eV (50 J)
- Acceleration sites at highest energy are currently unknown
- At Extreme High Energy (EHE) cosmic ray protons will interact with intergalactic IR photons to produce guaranteed source of EHE neutrinos (GZK effect)
- GZK effect is understood and cosmic rays at these energies have been detected
- There is some uncertainty in the absolute flux of EHE cosmic rays
- Additional sources may also exist, increasing fluxes
- By the time PRIDE could arrive at Europa (c. 2030?), two decades of observations should significantly reduce the uncertainty in the EHE neutrino flux

Primary Cosmic Ray Energy Spectrum



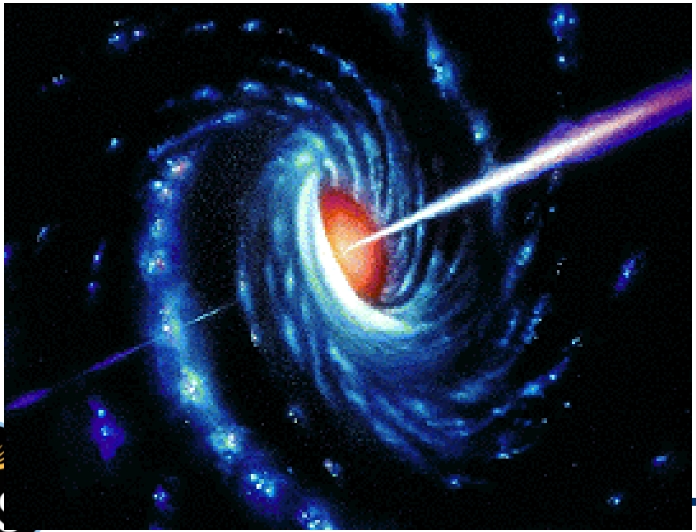
Astrophysical Neutrino Sources

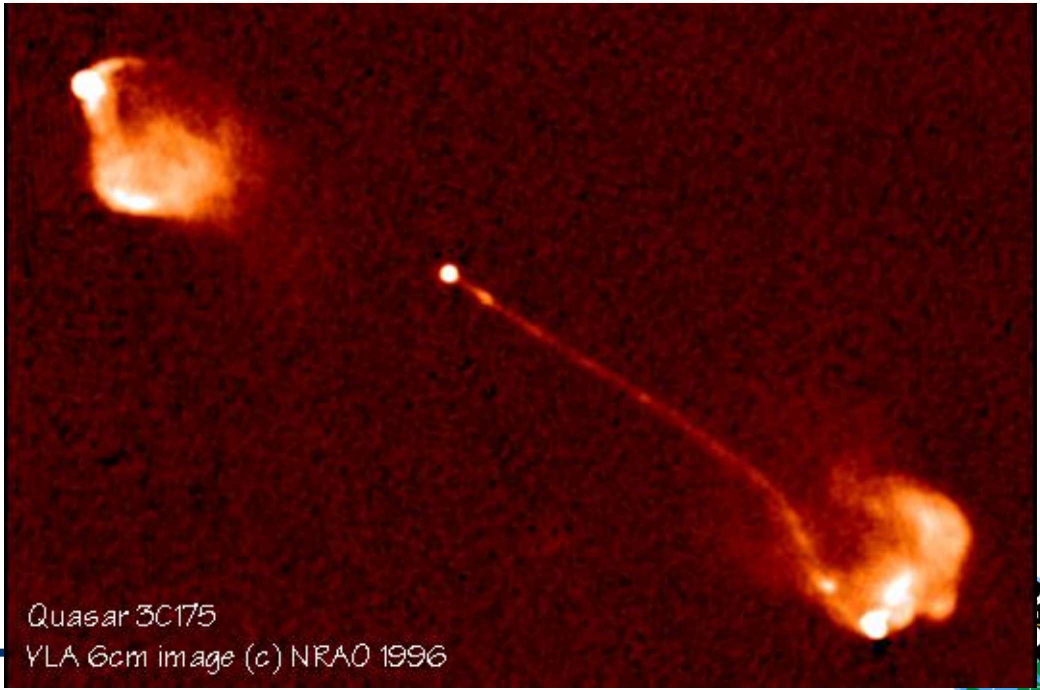
- Cosmic Accelerators
  - Protons accelerated to high energy interact with matter near source to produce high energy ν's and photons
  - Photons are absorbed by intervening matter
  - Some protons arrive at Earth as cosmic rays



Active Galactic Nuclei (AGN)

- A very luminous galaxy at huge distances with a massive black hole (10^8 M_{sun}) at its center
  - distances of 100's to 1000's of MPC
  - highly (10X) variable over short time scales (days to weeks)
  - often show superluminal jets
- Large fraction of energy emitted in gamma rays
  - > 20 detected above 10^8 eV
  - 2 detected above 10^{12} eV





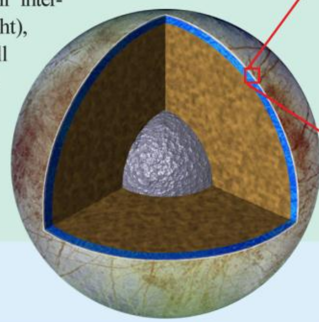
Can JEO determine the thickness of Europa's ice shell?

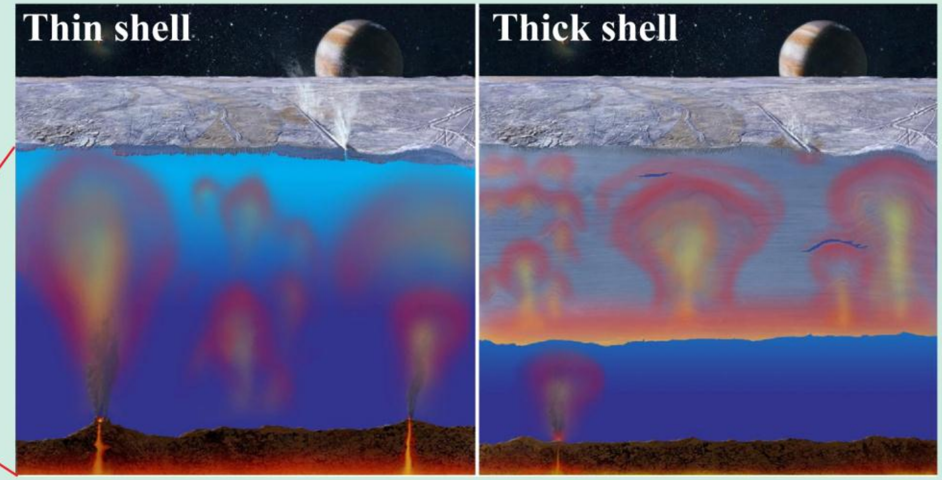
On Thick or Thin Ice?

Despite more than a decade of study of the Galileo data, the fundamental issues of the thickness of Europa's ice shell remain uncertain to over an order in magnitude [*Kattenhorn and Billings 2005*]. Estimates range from just a few kilometers [*e.g. Greenberg et al. 2000*] to several tens of kilometers, or more [*Pappalardo et al. 1999*]. The thickness of the ice shell is important to understanding Europa's potential habitability, for example, in controlling the types of geological processes that affect material exchange between the ice shell and ocean.

Galileo gravity data suggest that Europa is differentiated into an iron core, rocky mantle, and an H_2O-rich outer shell ~100 km thick, consisting of an ice shell and a liquid ocean. Galileo imaging data reveal a wide variety of enigmatic surface features.

In a thin ice shell interpretation (near right), ridges are sites where liquid water has squeezed out onto the surface, and chaotic terrains form by melt-through of the ice shell from strong hydrothermal plumes below [*Greenberg et al. 2000*]. In a thick ice shell interpretation (far right), Europa's ice shell is convecting and localized partial melting can occur [*Pappalardo et al. 1999*].

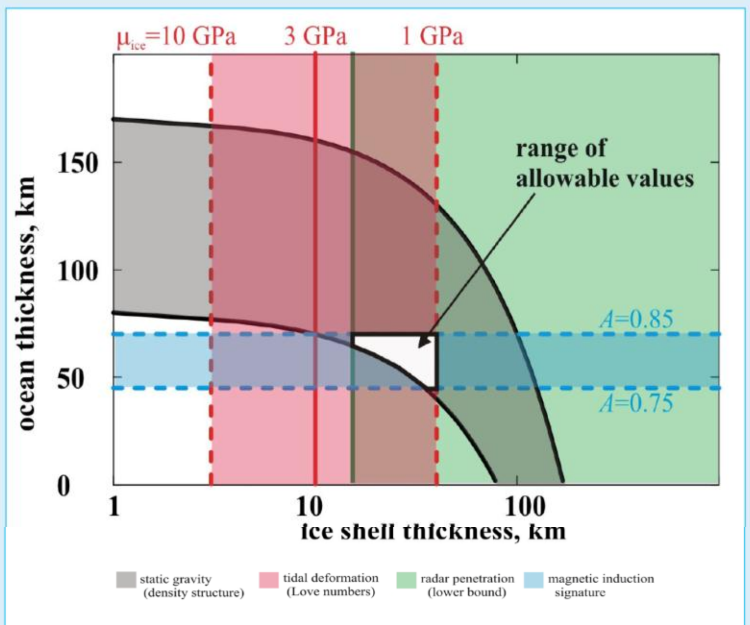




A hypothetical example using geophysical techniques

Geophysical measurements are non-unique. Nevertheless, using a combination of carefully planned geophysical techniques, JEO can constrain the thickness of Europa's ice shell.

Here is presented an example of how a combination of (hypothetical) JEO measurements can be used to constrain the ice shell thickness. Based on the bulk density and moment of inertia of the satellite (derived from flybys by JEO and previous spacecraft), the thickness of the water + ice layer may be obtained (gray shading) [*Anderson et al. 1997*]. The uncertainties arise mainly from our lack of knowledge of the density of the rocky interior (the bulk density is already well known).



Gravity and topography measurements

Measuring the time-variable gravity and topography gives the k_2 and h_2 Love numbers, respectively. Hypothetical Love number constraints here (red shading) assume observed h_2 and k_2 of 1.202 and 0.245, respectively, and constrain shell thickness as a function of rigidity μ_{ice} [*Moore and Schubert 2000*]. The hypothetical values assumed here are characteristic of a moderately thick ice shell.

In the example shown, the ice shell deformation is sufficiently large that a shell thickness in excess of 40 km is prohibited. Determining both k_2 and h_2 constrains the thickness significantly more than either value can alone. The ratio of h_2/k_2 is quite different depending on whether a subsurface ocean exists or not, and provides an additional test of the ocean's existence.

Radar Sounding

A lower bound on the ice shell thickness may be derived using ice-penetrating radar observations. The base of the ice shell is hard to image because warm ice is radar absorptive; however, even a non-detection of the ice-water interface allows a lower bound to be placed on the shell thickness. Here, a tectonic model of ice shell properties is assumed [*Moore 2000*], resulting in a radar penetration depth (and lower bound on shell thickness) of 15 km (green shading).

Magnetometer data

Multiple-frequency magnetic induction signatures (blue shading) constrain ocean thickness [*Khurana et al. 2002*]; here a hypothetical dimensionless induction signal A = 0.75–0.85 and an ocean conductivity of 2 S/m are assumed, resulting in an ocean thickness in the range 45-70 km.

This particular (hypothetical) set of observations results in a range of acceptable ice shell thicknesses (15 to 40 km) and a range of acceptable ocean thicknesses (45-70 km). A different set of observations would result in different constraints, but the main point is that the combined constraints are more rigorous than could be achieved by any one technique alone. JEO will provide the measurements needed to constrain the thickness of Europa's ice shell.

Ice Depth Measurements

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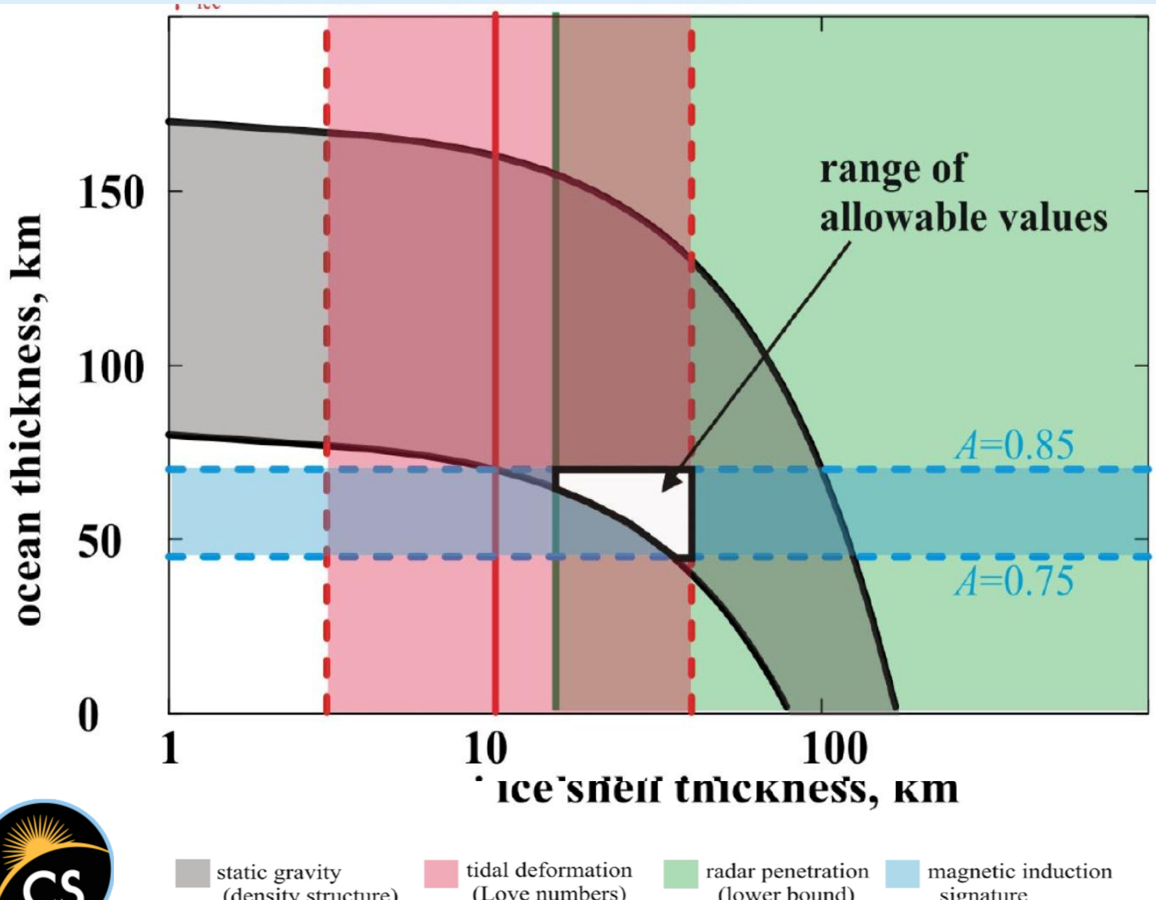
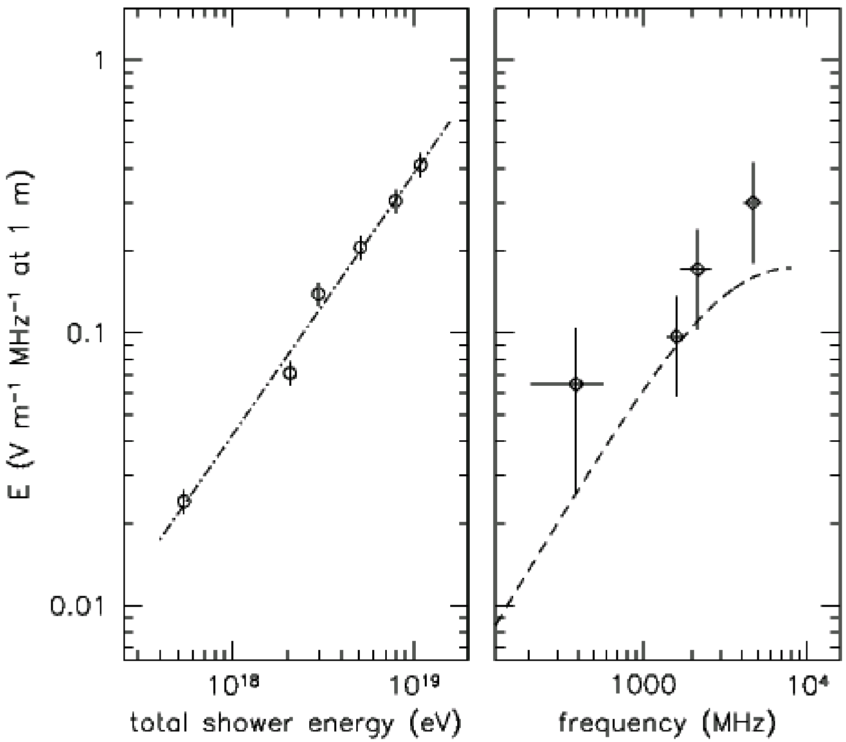


- **Example using possible measurements from a proposed large planetary flagship mission (JEO) results in 15-40 km range**
- **Opportunity for improvement from novel measurements concepts**

Askaryan effect experimentally confirmed

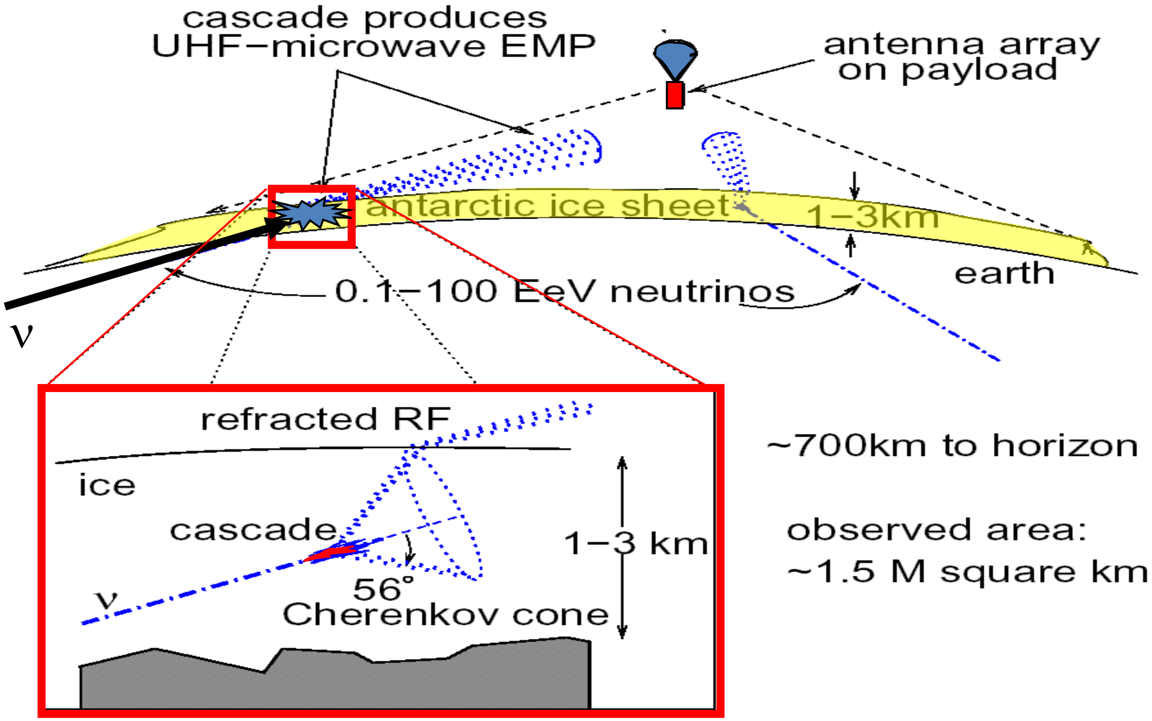
Experiment at SLAC using 3.6 tons of Si sand target
Bunches of GeV photons, total E = 10^{19} eV
All major radio emission properties confirmed:
charge excess, coherence, pulse strength, polarization

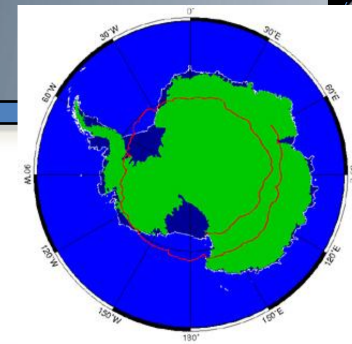
D. Saltzberg et al., Phys. Rev. Lett. **86** (2001): 2802-2805

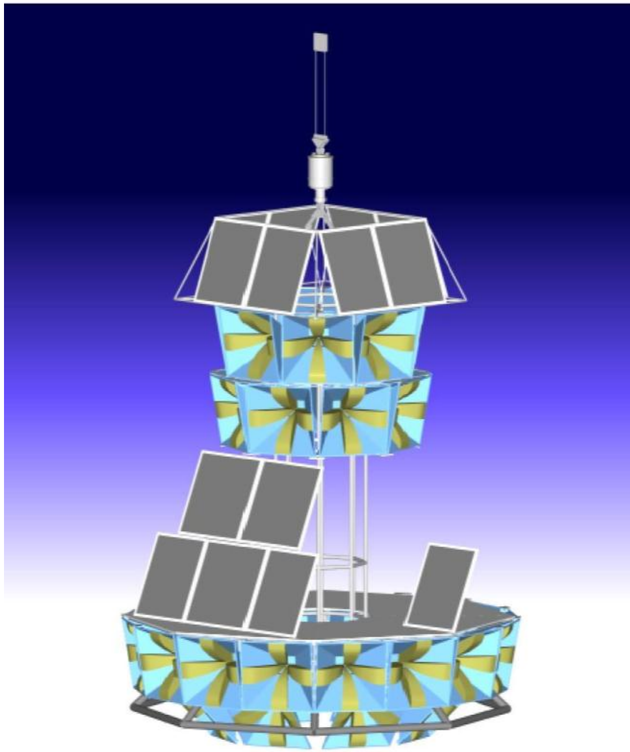


ANITA = ANtarctic Impulsive Transient Antenna

Balloon circling at 37 km above Antarctica to detect radio signals from the ice







From S. Barwick, APS talk 04/2004

Flights Dec. 2006 and Jan. 2009

ANITA-lite test flight $\rightarrow$ ν flux limit

12/06: 18 days at float altitude $\rightarrow$ 1.25 revolutions

APL

Existing experiments → flux limits
RICE = Radio Ice Cherenkov Experiment

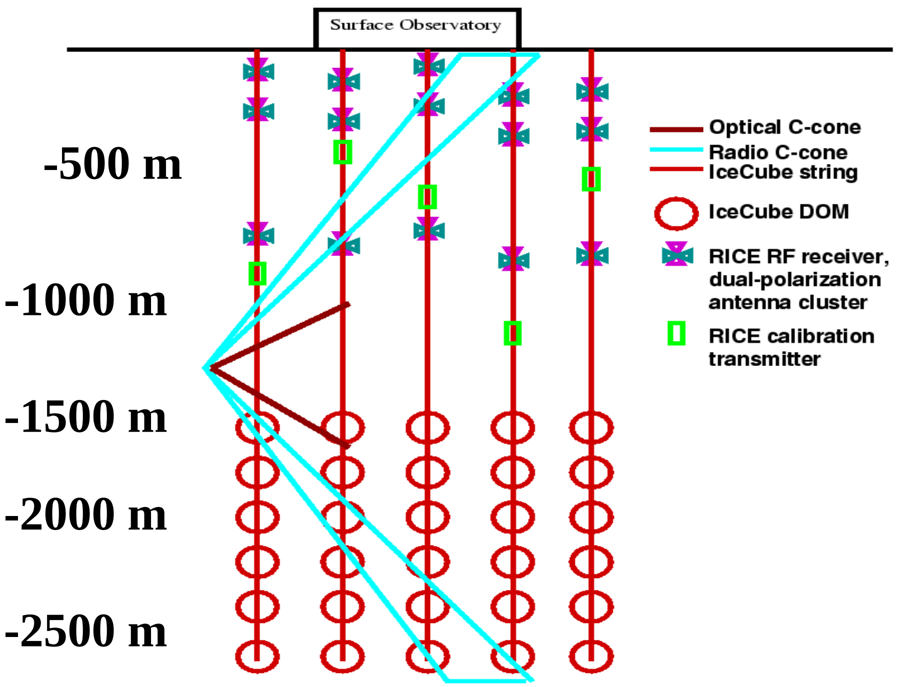
Dipole array @ Amanda
in South pole ice

- Use AMANDA holes
- 18 Receivers (10 cm dipole)
- 5 Transmitters
- 3 Horns (INR mark)
- 100-300 m depth
- 200x200x200 m^3 cube
- DAQ, PCs, Pulse Generator
- 1 dry hole

Absorption function of temperature
For cold ice 0.1-1.0 GHz best
Allows radio signal to travel > 1 km

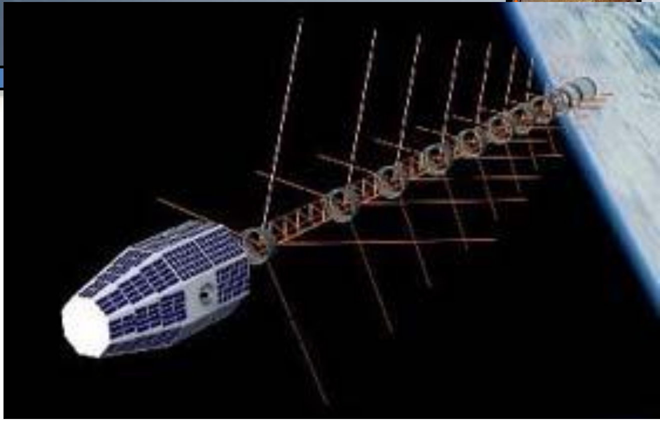
3 years data taking
→ ν flux limit

RICE – CUBE 20??



Project under discussion
holes may be separate from IceCube
V_{eff} growth ~10-25

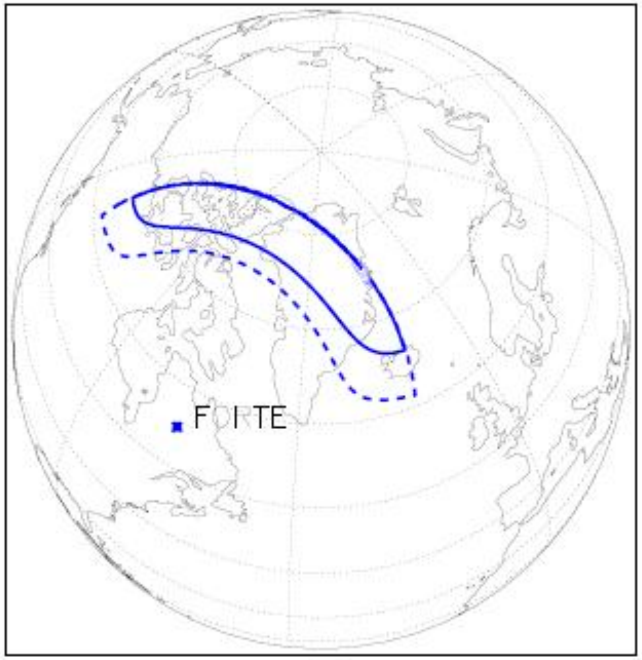
FORTE = Fast On-orbit Recording of Transient Events



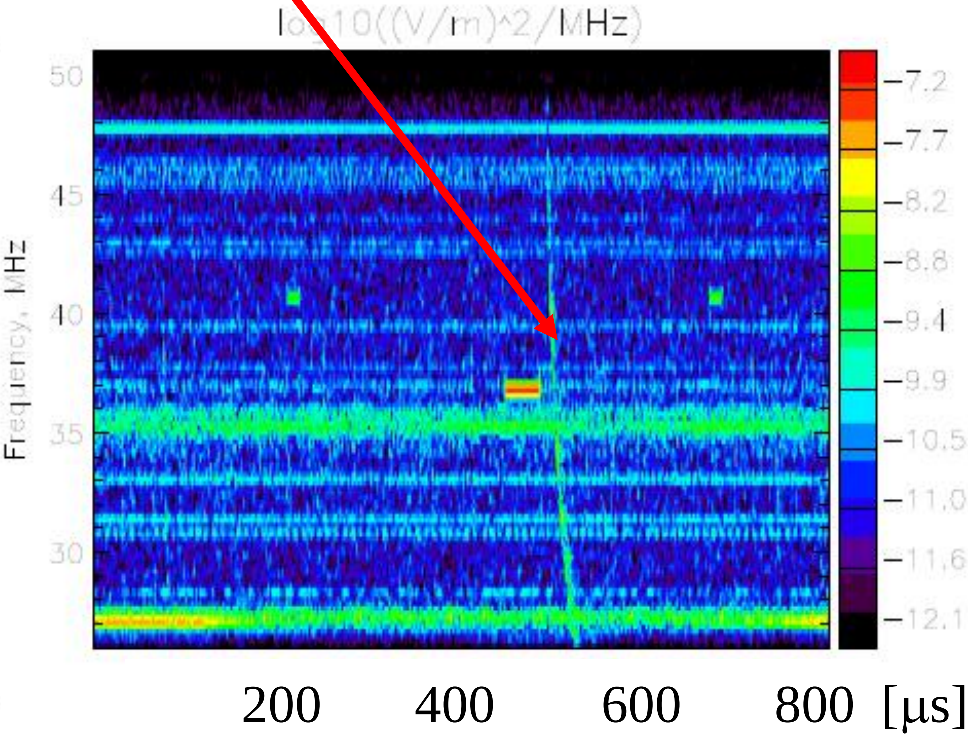
Transient EM-signals from Earth in satellite

- Only ~3 days net exposure
- Lightning, ionosphere, radio/TV …
- Events from Greenland ice background + maybe 1 candidate

→ Flux limit



Lethinen et al., astro-ph/0309656



Proposed Lunar Orbiter

- Sensitivity of radio equipment determines threshold energy

$$E_s^{th} = 8.55\times 10^{20}\,\frac{R}{R_L}\,\frac{\nu_0}{\nu}\left[1+\left(\frac{\nu}{\nu_0}\right)^{1.44}\right]\sqrt{\frac{N_\sigma^2 T_{\text{noise}}}{\Delta\nu\, A_{\text{eff}}}}\quad eV$$

signal $\geq N_\sigma^2 (=25) \times$ noise

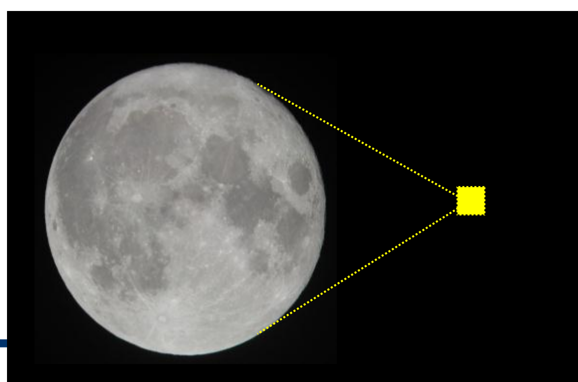
$$T_{\text{system}} = 300\,K,\quad T_{\text{galactic}} = 1.5\times 10^6 \left(\frac{10\,MHz}{\nu}\right)^{2.2} K$$

effective antenna collection area A_{eff}

- Field-of-view and sensitivity are complementary quantities

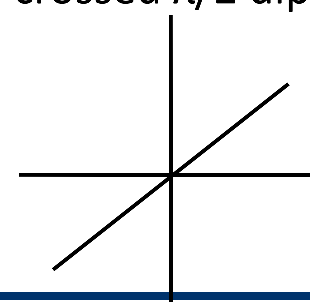
- We have focused on two antenna configurations:

beam-filling



isotropic “tripole”

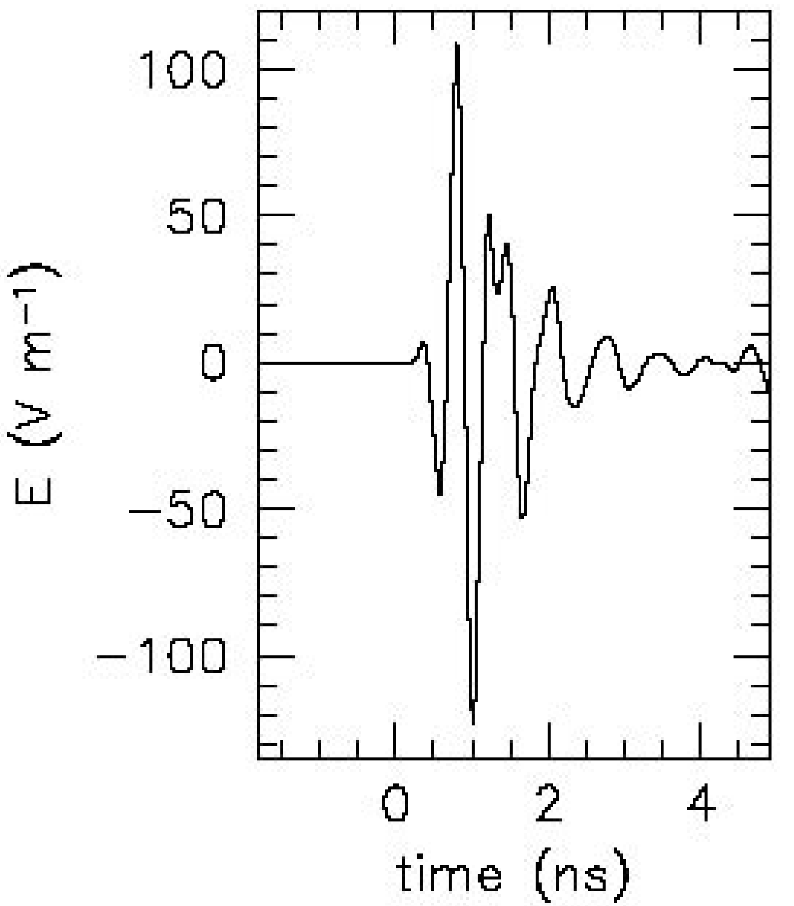
(3 crossed λ/2 dipoles)



Signal Characteristics

- Significant signal power at large frequencies (1-2 GHz)
- Digitization at ~1 GHz frequencies required
- No commercial solution – too much power/cost
- A possible approach to overcome these issues is described later

Typical PRIDE time domain pulse



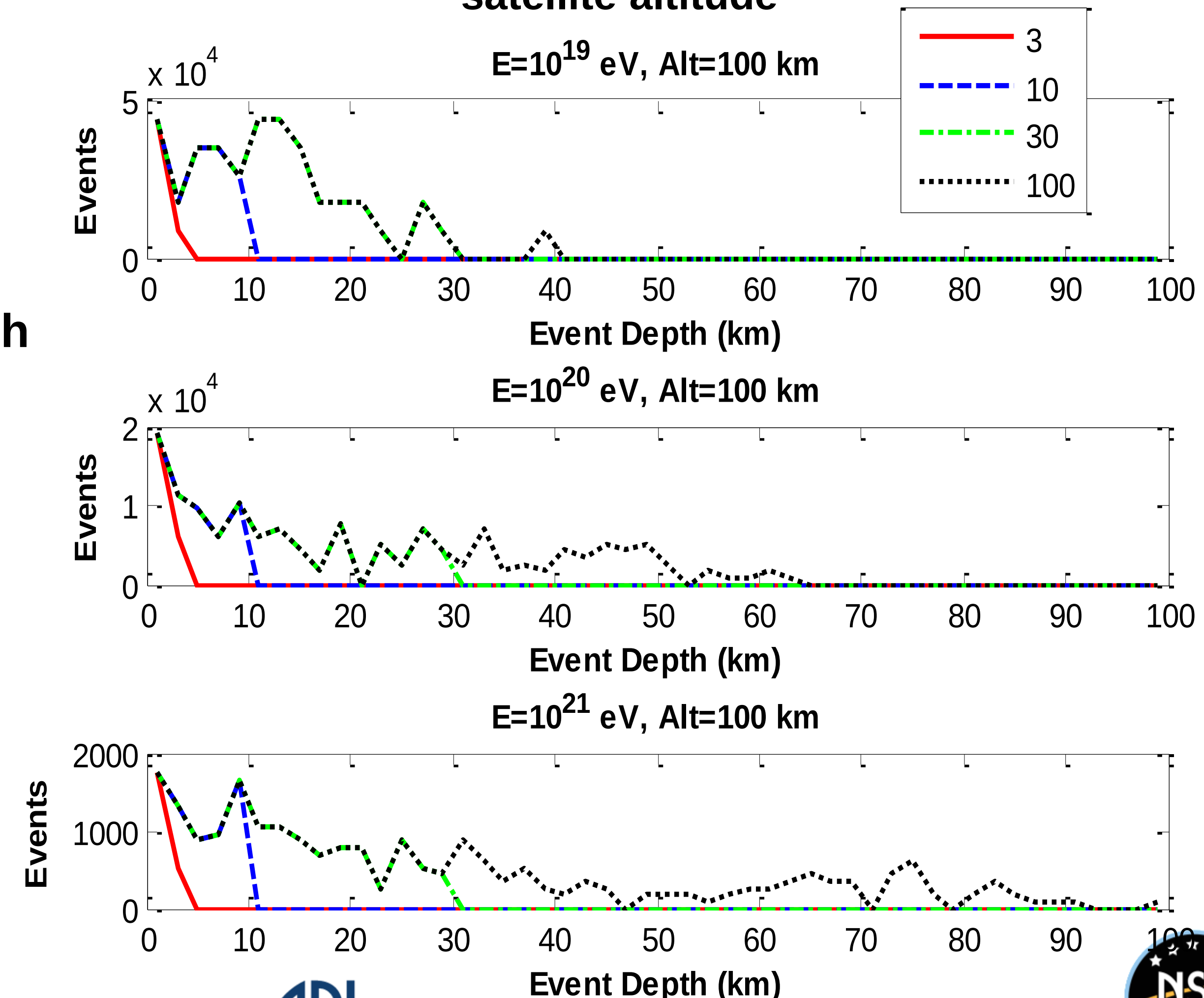
Thermal Background

- Background due to thermal emission is roughly the thermal energy divided by the effective antenna area kT/A
  - There is also a term like $\Delta t \Delta v$ but for the events being considered here $\Delta t \Delta v \sim 1$
- Receivers will be staring at Europan ice at ~100K
- Assuming an effective area of about 0.05 m^2:
  - kT/A ~ 2.8×10^6 Jy
  - SNR ~ 2 for small (.05 m^2) antenna at 600 km
- Conclusion: making use of the full visible ice cap may be challenging for a small instrument, even with low noise temperatures, but is not impossible

Events vs. Ice Depth

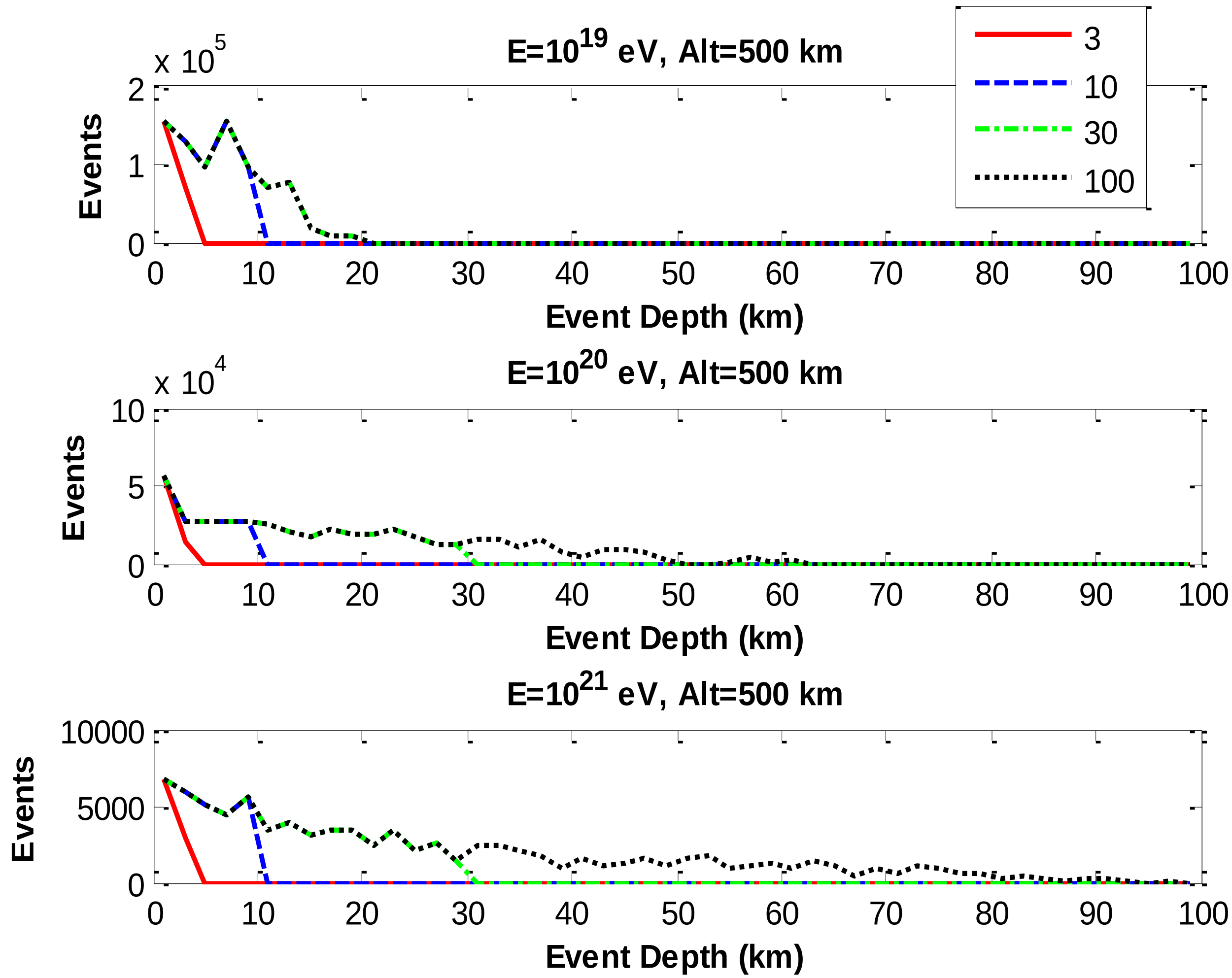
- Plots show event depths for a satellite altitude of 100 km and neutrino energies of 10^{19}, 10^{20}, and 10^{21} eV.
- In each graph the depth of detected events is shown for ice sheet thicknesses of 3, 10, 30, and 100 km.
- At higher energies, additional events are detected as ice depth increases

Depths of detected events vs. neutrino energy and satellite altitude



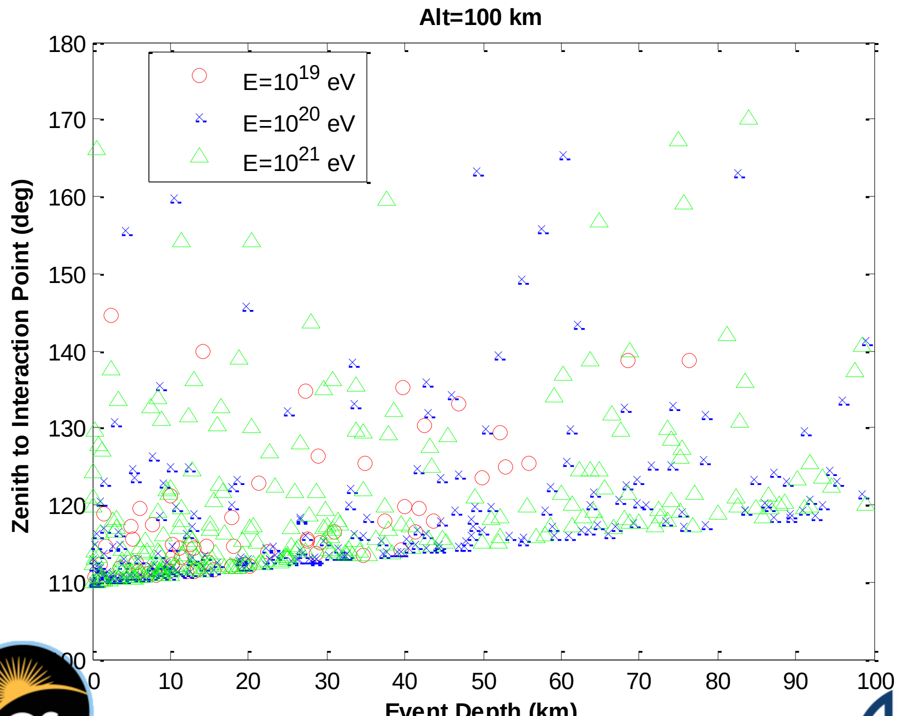
Events vs. Ice Depth

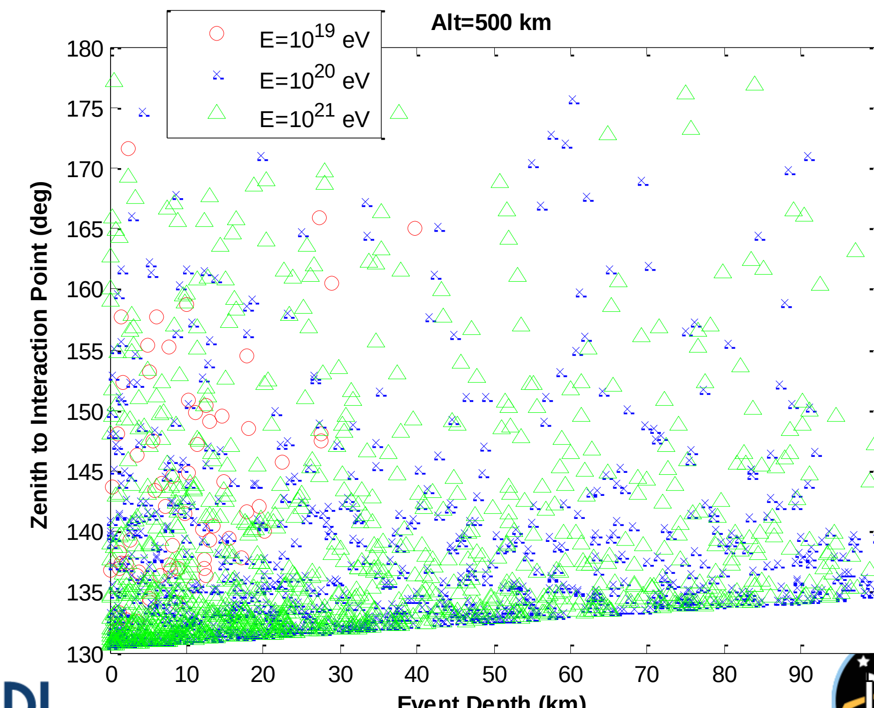
- The same graphs as the previous page, but showing results for a satellite altitude of 500 km.
- Again, additional events are detected as ice depth increases.
- Question: can we identify these events as coming from deeper ice?



Zenith Angle

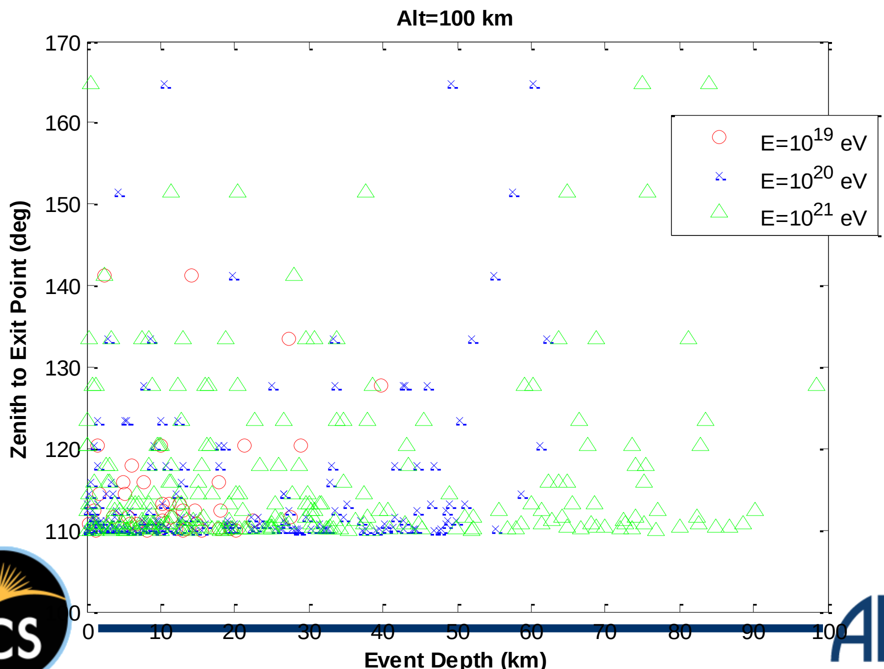
- Scatter plots of zenith angle from a satellite to the interaction point vs. event depth for a 100-km-thick ice sheet, for neutrino energies of 10^{19}, 10^{20}, and 10^{21} eV.
- Most events come from a narrow angular range, but the minimum zenith angle increases with ice depth, and it appears that the events may cluster near the minimum less for greater ice depths.

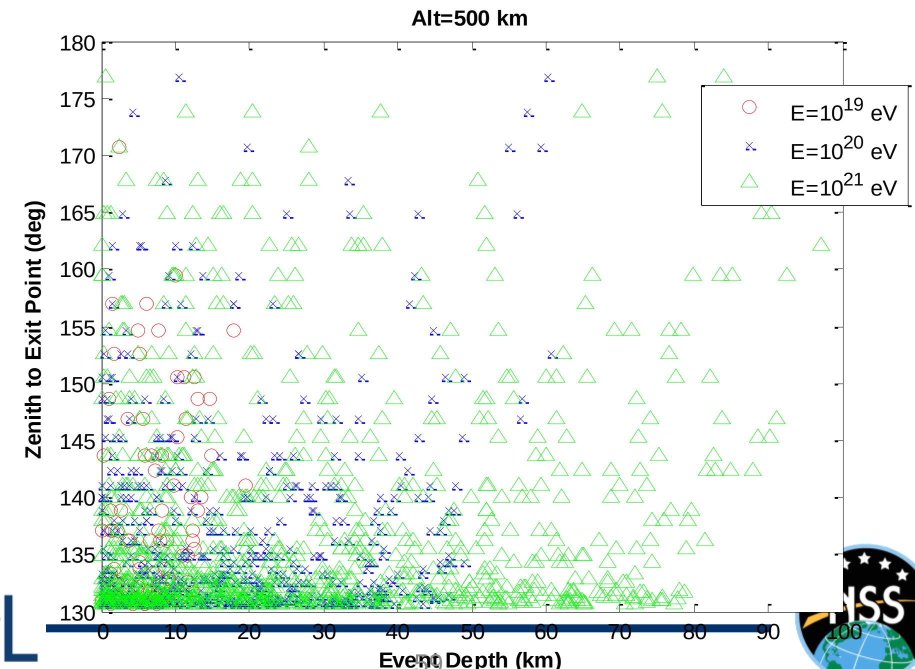




Observed Zenith Angle

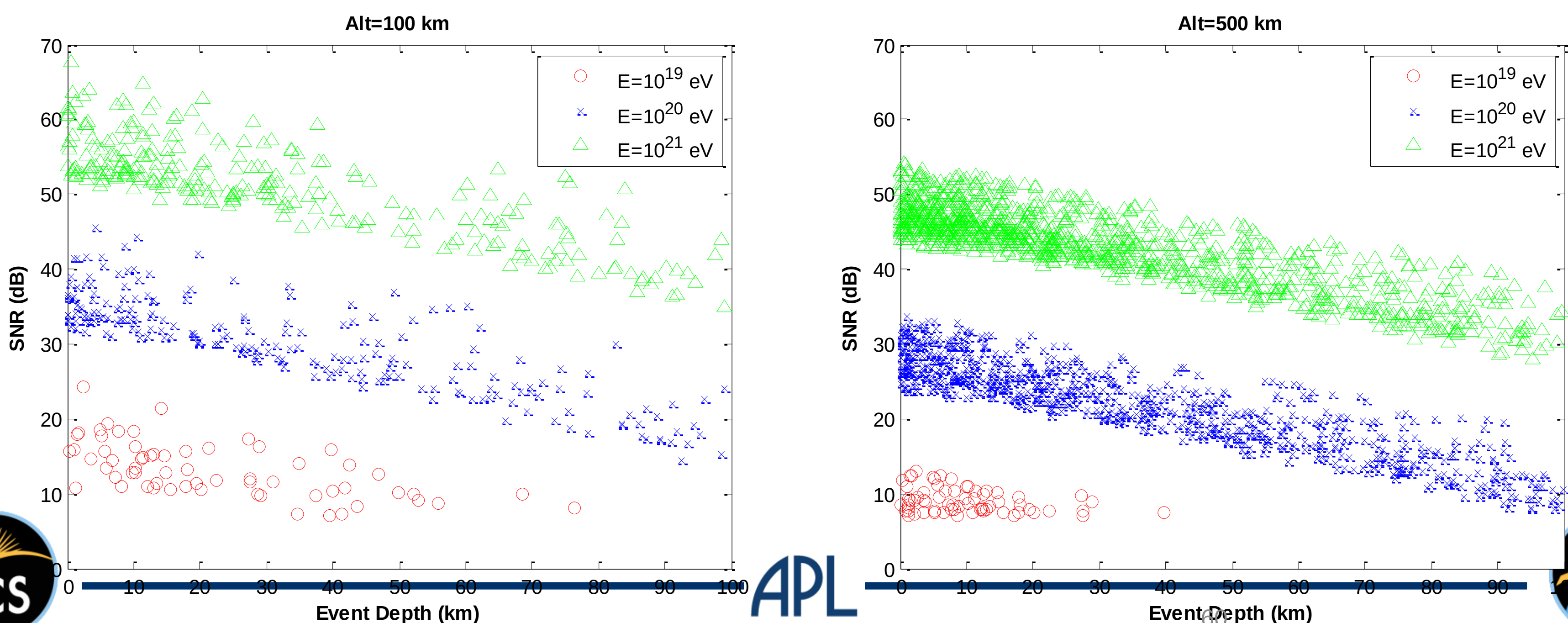
- Scatter plots of observed zenith angle
- Most events arrive from a narrow annulus near the horizon due to refraction at the surface: nontrivial to determine depth based upon observed zenith angle distribution.
  - It appears that at greater depths a higher fraction of events may arrive from larger zenith angles.
  - In addition, surface roughness causes some energy to exit the ice with a lower refraction angle, making the real distribution somewhere between this slide and the previous





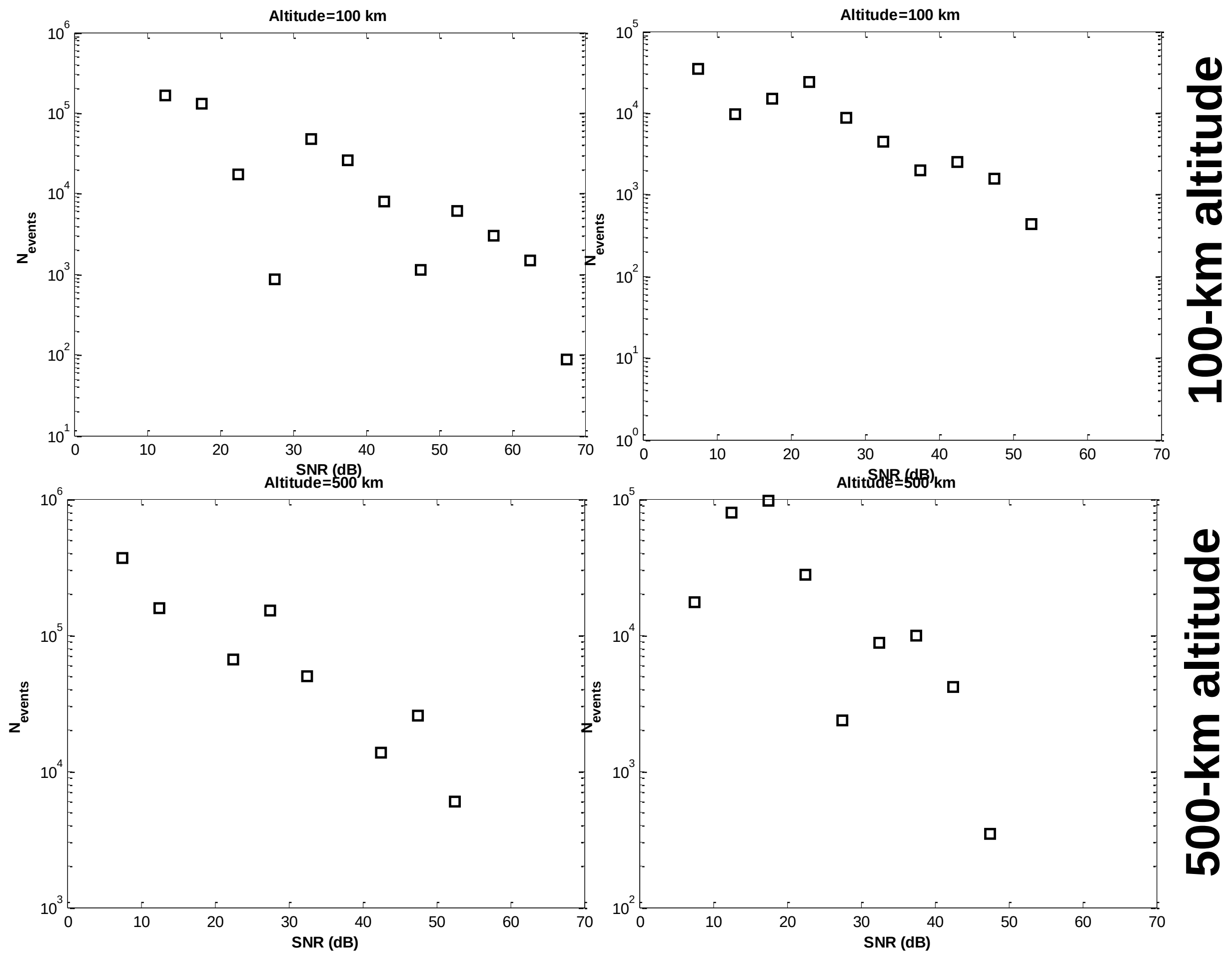
Intensity Distribution

- Scatter plots of SNR vs. event depth for a 100-km-thick ice sheet, for neutrino energies of 10^{19}, 10^{20}, and 10^{21} eV, for 100 km and 500 km satellite altitudes
- At any given event depth, the maximum signal size is determined by the maximum observed neutrino energy
- If energies above a certain limit become too rare to observe due to decreasing source flux, it may be possible to determine the ice sheet depth from the distribution of event sizes



Intensity Distribution

- Distributions of observed SNR for events originating at different depths in a 100-km-thick ice sheet
- Events are weighted by an E^{-2} spectrum.
- If events above 10^{21} eV become too few to detect (as an example), the fraction of large events appears lower for events at great depths than those at shallow depths, especially for the 100 km satellite altitude.



events originating at depths < 20 km

events originating at depths > 50 km