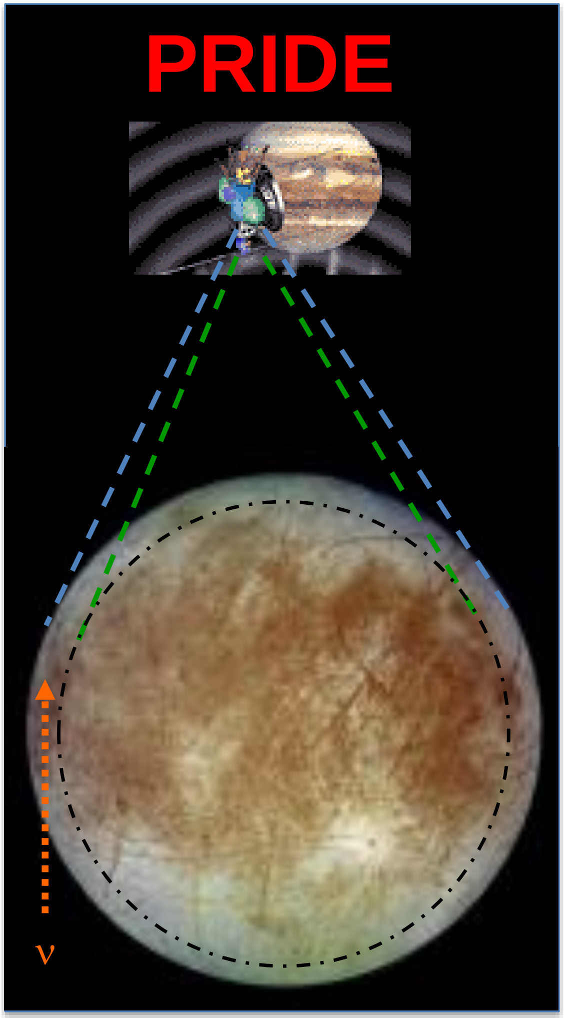

PRIDE – Passive Radio Ice Depth Experiment - An Instrument to Measure Outer Planet Lunar Ice Depths from Orbit using Neutrinos

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University of California / Irvine

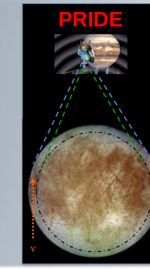
THE OHIO STATE UNIVERSITY

JPL Jet Propulsion Laboratory California Institute of Technology

KU THE UNIVERSITY OF KANSAS

APL JOHNS HOPKINS UNIVERSITY Applied Physics Laboratory

Overview

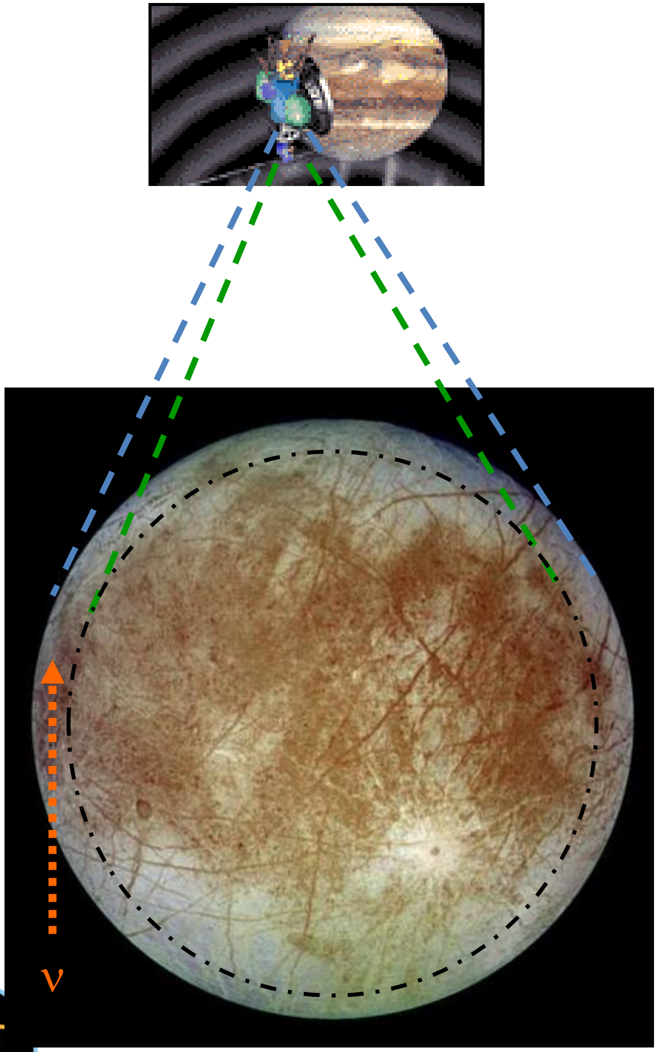


- Investigated a technique for remotely sensing ice depths on icy moons
  - Using EHE neutrino “illumination” and passive RF technology (Askaryan Effect) on an orbiting satellite
- Performed a high level feasibility study of an outer planet mission instrument (“PRIDE”).
- No major showstoppers found, 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

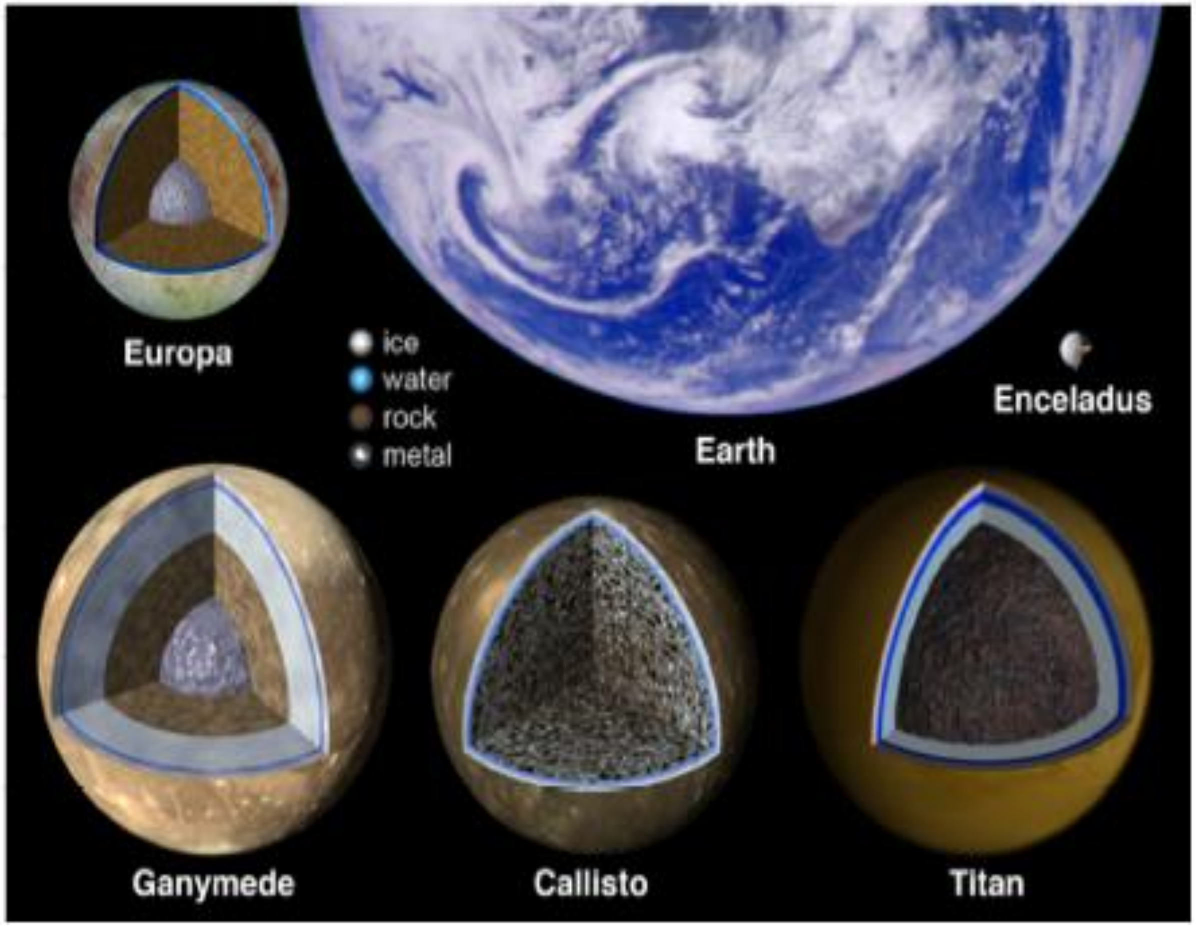
Science Goal



- Basic Concept
  - Use passive RF receiver on Europa (or other outer planet ice moon, e.g. Enceladus) 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

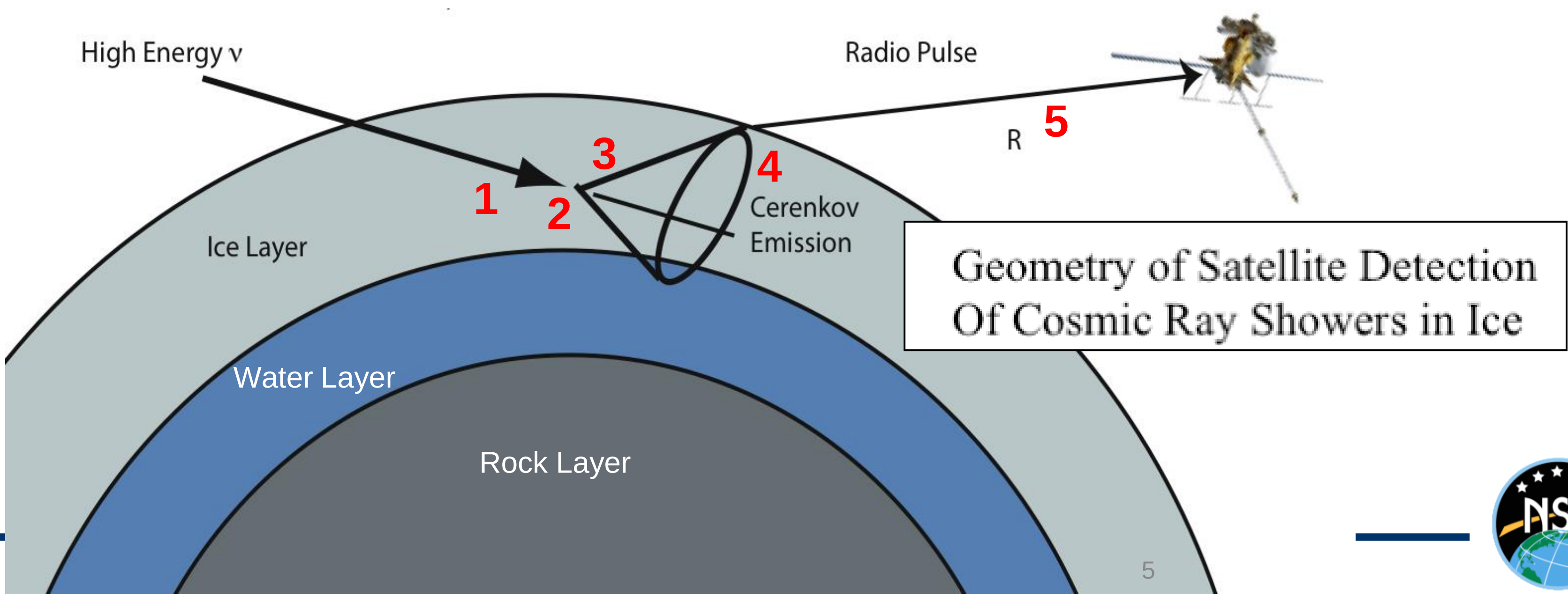
- The "Ocean Worlds" - moons of Jupiter and Saturn that harbor oceans under an icy shell.
- Understanding the evolution and structure of these ice covered ocean moons yields important clues to how conditions hospitable for life can form in the universe.
- [Figure taken from the NASA Jupiter Europa Mission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



Planetary bodies shown to scale

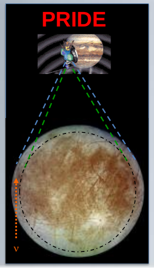
Basic Concept

- Use radio receiver technology to detect RF Cerenkov emission (Askaryan Effect) from neutrino interactions in the ice sheet
  - Peaks at ~0.2-2 GHz and is detected by an orbiting spacecraft
- Deeper ice sheets will produce a greater number of detectable events than thinner ice sheets
- The zenith angle and size distributions (and possibly other characteristics) of the events should also depend upon the ice sheet thickness

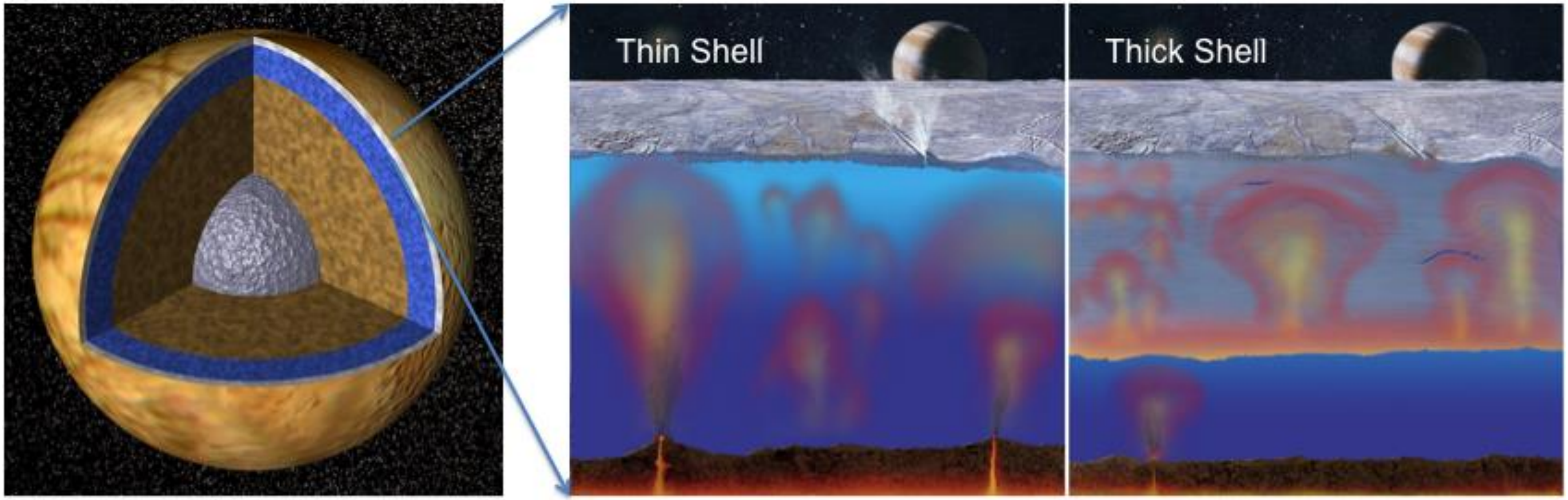


Poster Child for PRIDE: Europa

Galilean Moon of Jupiter



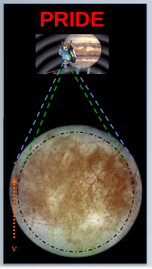
- Smallest of the Galileans. (R=1560 km, a little smaller than Earth's Moon)
- Outer planet moons covered with ice: possibly 10's of km thick, covering watery oceans where life may exist
- Sensing ice depth on Outer Planet moons, especially Europa with an ancient underice ocean, is a high priority science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



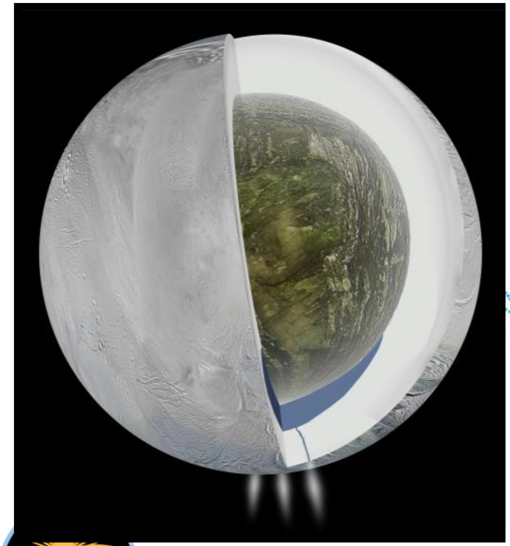
Europa is covered with a shell of ice whose thickness is unknown and is a source of speculation among planetary geologists. Shown above is a cutaway of Europa showing a shell of ice covering a deep ocean. To the right is an artists conception of thin and thick ice shell geologies on Europa. Tidal forces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

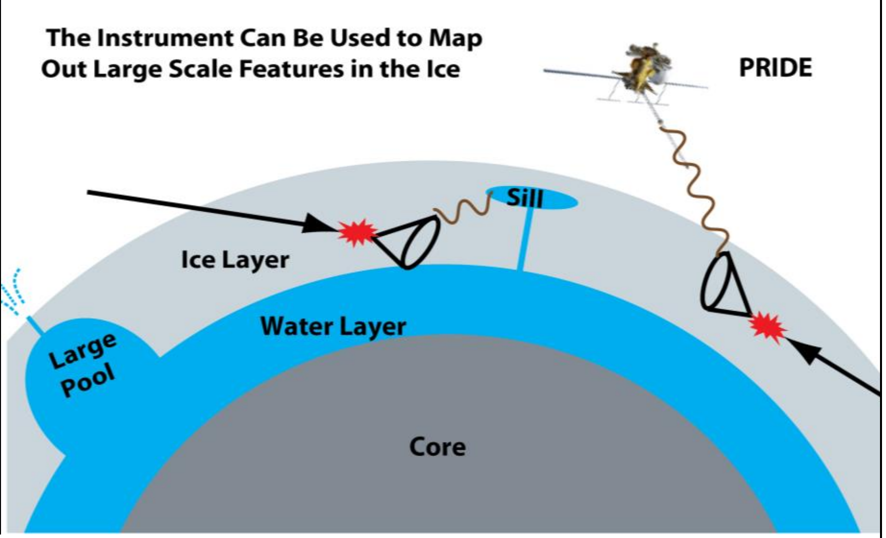
Poster Child 2: Enceladus

Global Feature Delineation



- **Small Saturnian Ice Moon: R=252 km (transparent to ν's into EHE range)**
- **Using gravimetric data from *Cassini* flybys obtained from 2010–12, analysis implies that Enceladus likely has a liquid water ocean beneath its frozen surface**
- **Analysis suggests top of ocean lies beneath a 30-40 km thick ice sheet. Ocean is ~10 km deep.**
- **Not clear if ocean exists only in south polar region, stretches to the equator, or into the northern hemisphere, but it appears to be thickest in the south polar region**
- Stevenson, D.J. et al. (2014-04-04). "The Gravity Field and Interior Structure of Enceladus". *Science* **344** (6179): 78–80.
- Shoji, D., Kurita, K., Tanaka, H.K.M., 2012. Efficiency of neutrino-induced radio measurements to inspect local areas of Enceladus, Icarus, 218, 555.





Water intrusions and embedded pools will block some direct RF signal paths and create additional reflected paths, causing signals and count rates to vary in different directions. By assembling the global directional signals and rates, a low resolution map of the ice can be constructed.

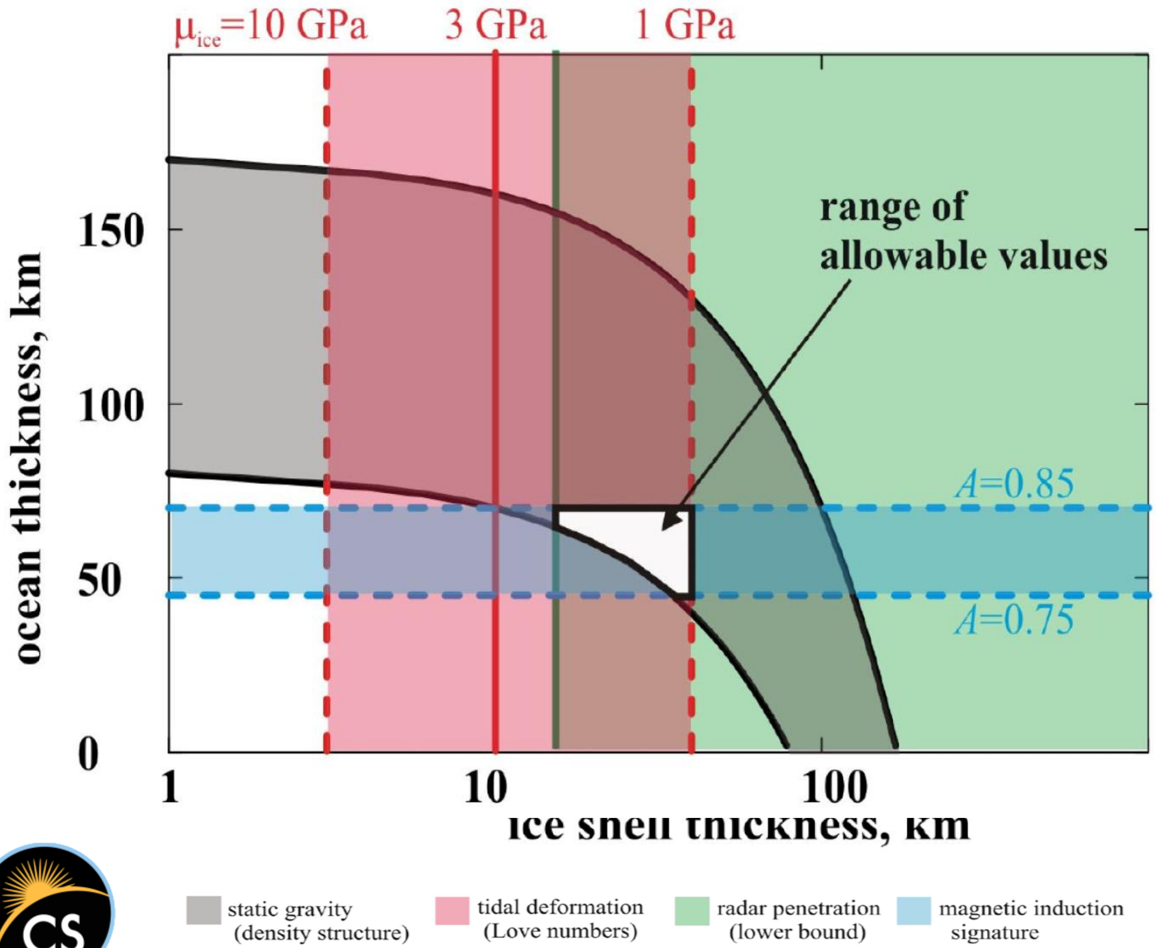
Ice Depth Measurements

- Current methods of estimating ice 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

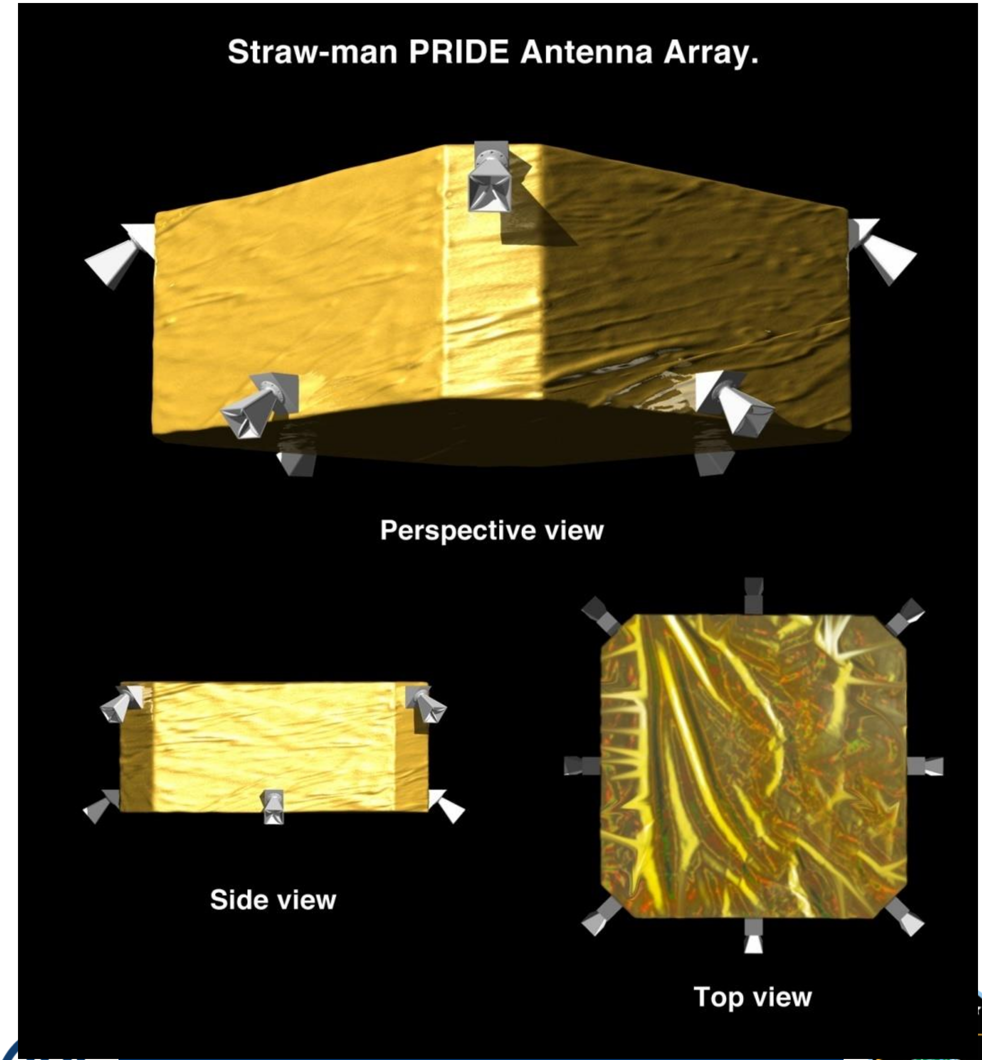
This particular (hypothetical) set of observations results in a range of acceptable ice shell thicknesses (15 to 40 km) and a range of acceptable ocean thicknesses (45-70 km). A different set of observations would result in different constraints, but the main point is that the combined constraints are 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]

Strawman PRIDE Antenna Array Concept

- 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



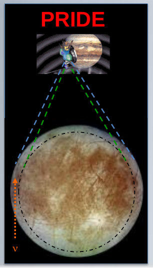
Instrument Summary

Comparison of Active Radar and Passive PRIDE Parameters

Parameter	Ice Penetrating Radar	PRIDE
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

Questions

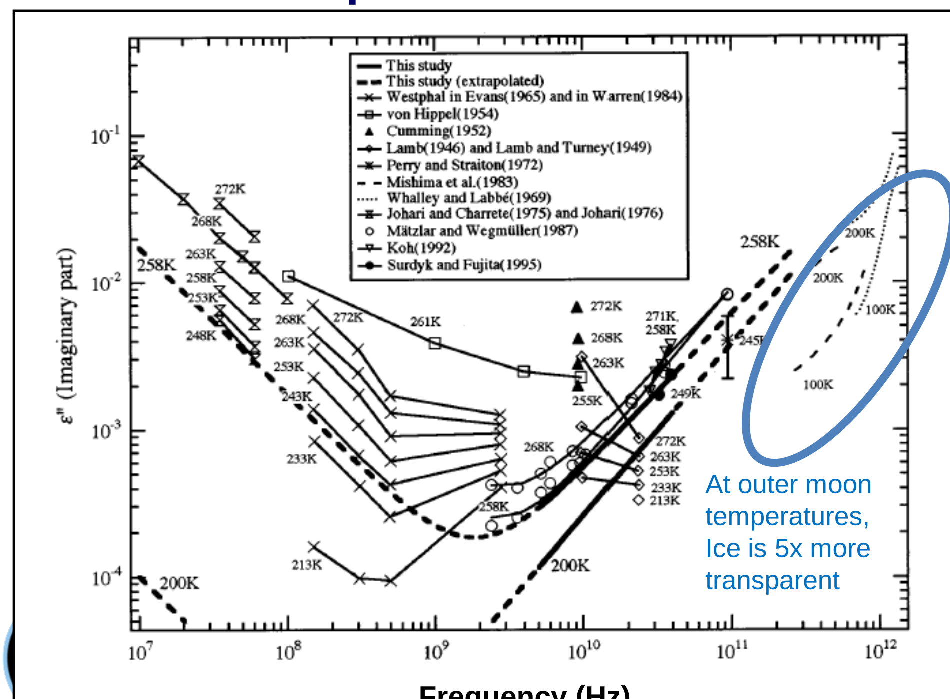


- Can this signal be exploited to sense the depth of the ice? (see also Shoji, et al., 2011).
- Are there problems with making an instrument that could perform these measurements on an Outer Planet mission?
  - Tough constraints on power, size, & mass
  - Backgrounds near Jupiter
- Initial PRIDE results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

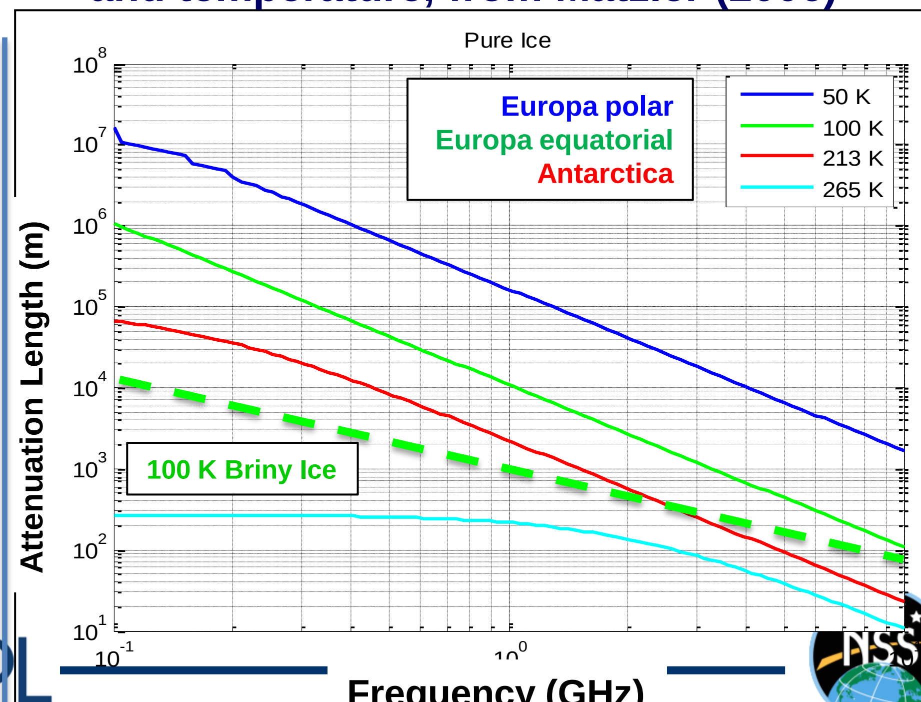
Pure Ice Transparency

- 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!

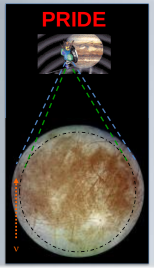
Experimental Results



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



Europa Event Simulation

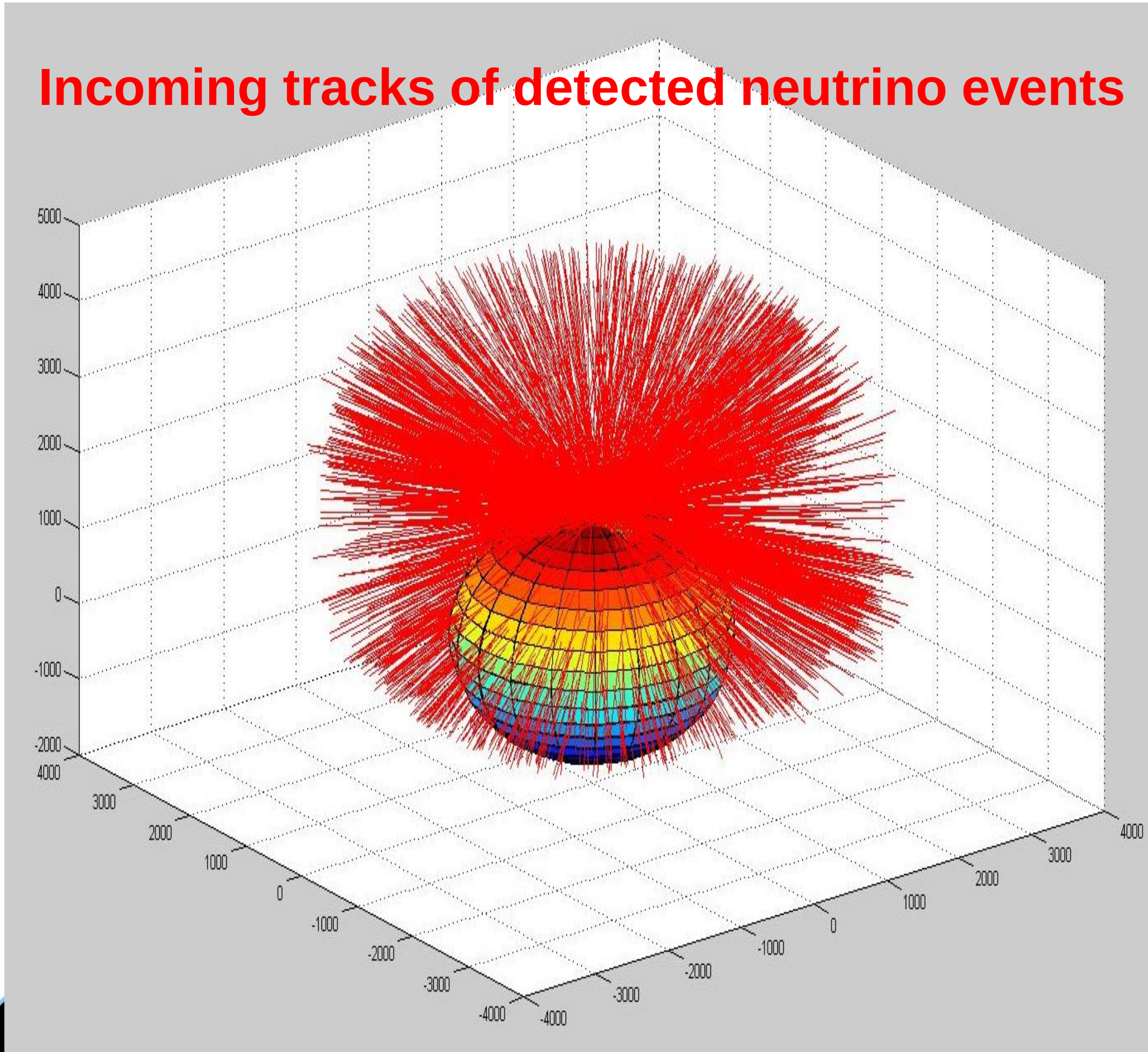


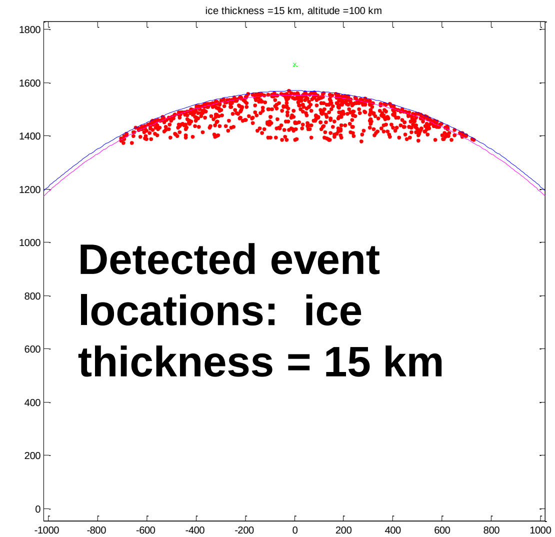
Monte Carlo simulation of the neutrino signal performed as a function of source spectrum, ice depth, satellite altitude, and detector characteristics

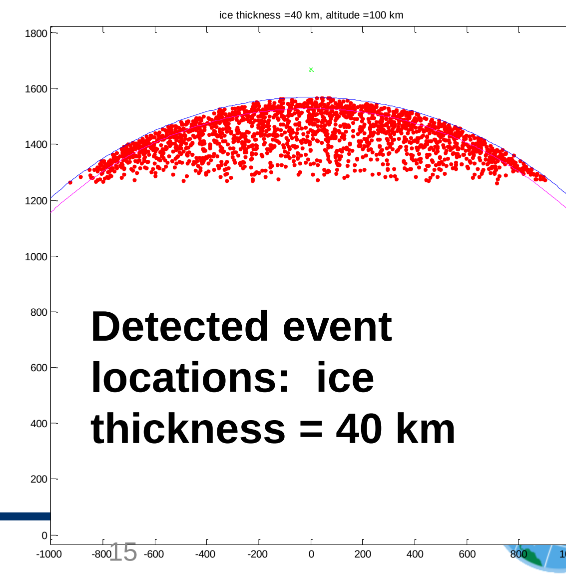
1. 10^5 simulated neutrinos were generated at random locations with random incident directions at energies of 10^{18}, 10^{19}, 10^{20}, and 10^{21} eV
2. Neutrinos were propagated through Europa along discrete 0.1-km steps until each either interacted or passed through Europa
3. For interactions, the 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
   - Simple parametric model of signal and thermal noise: detector modeled as a single antenna of area 0.25 m^2, central frequency = 600 MHz, and bandwidth = 600 MHz. Noise modeled as T=100K background
   - Result: $SNR \sim 10*(E_\nu/10^{19}\ eV)^2$ for Range = 400 km
   - 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

Simulation Results

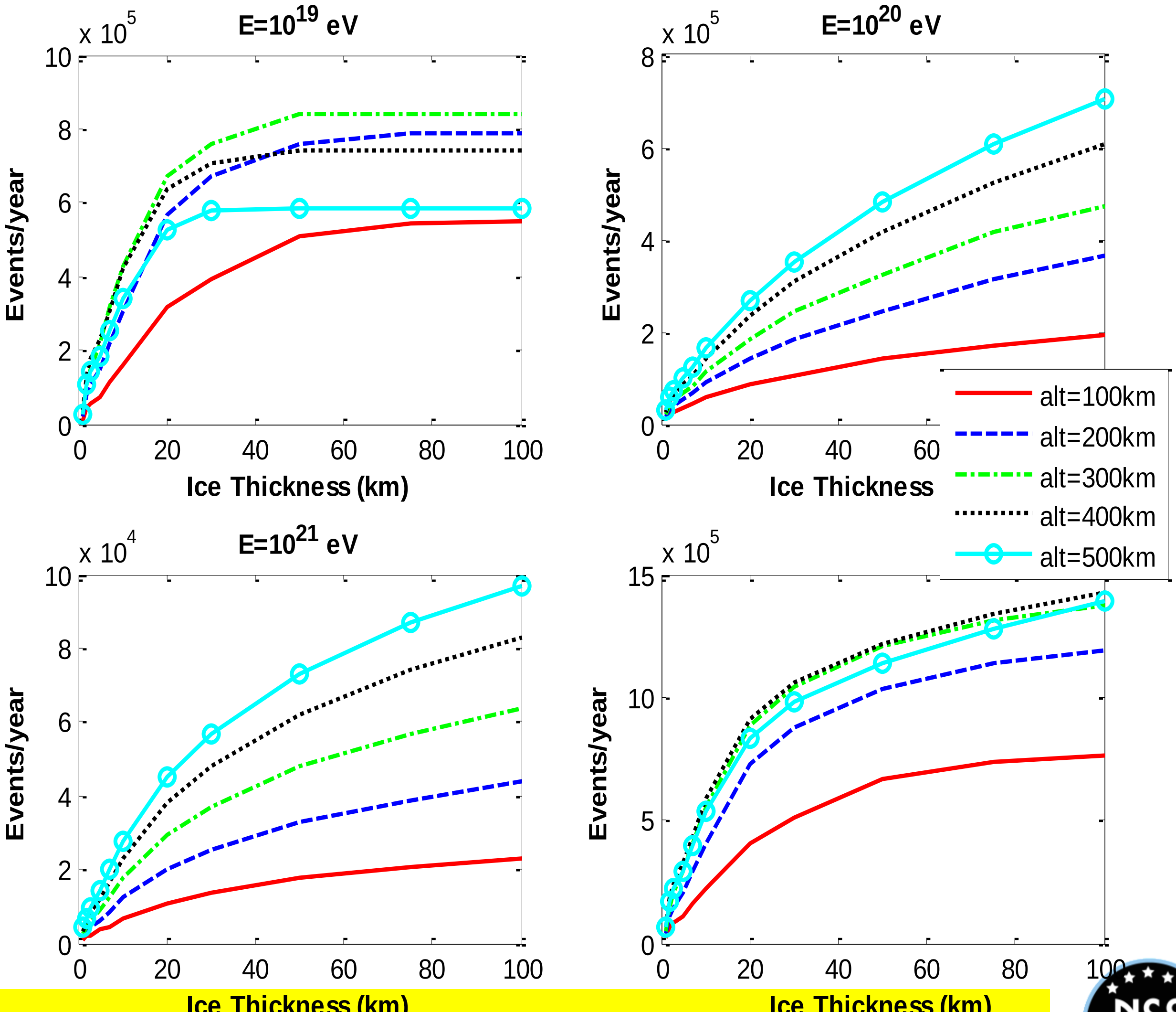






Detected Event Rate

- 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

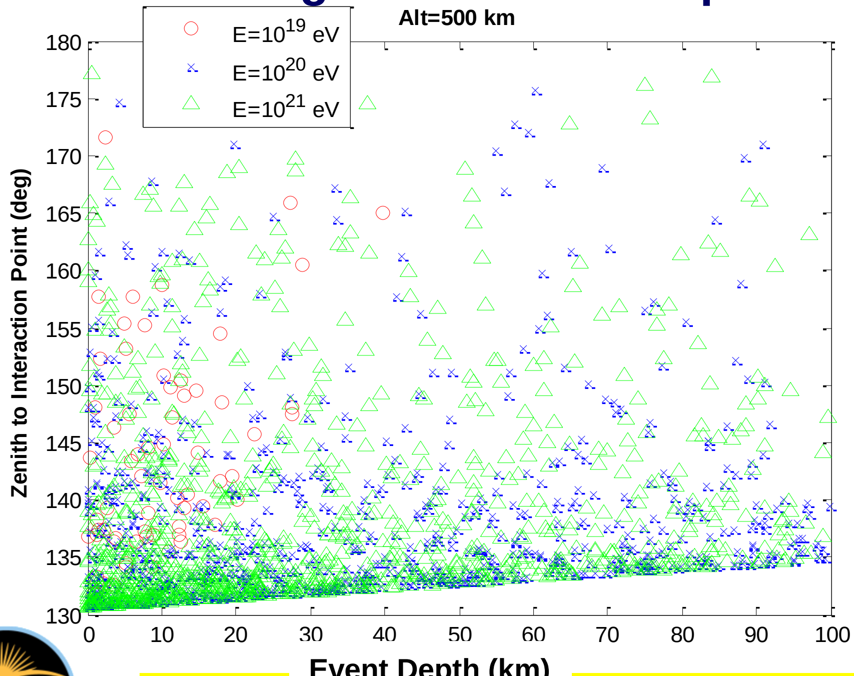


Event rate is very sensitive to ice sheet thickness

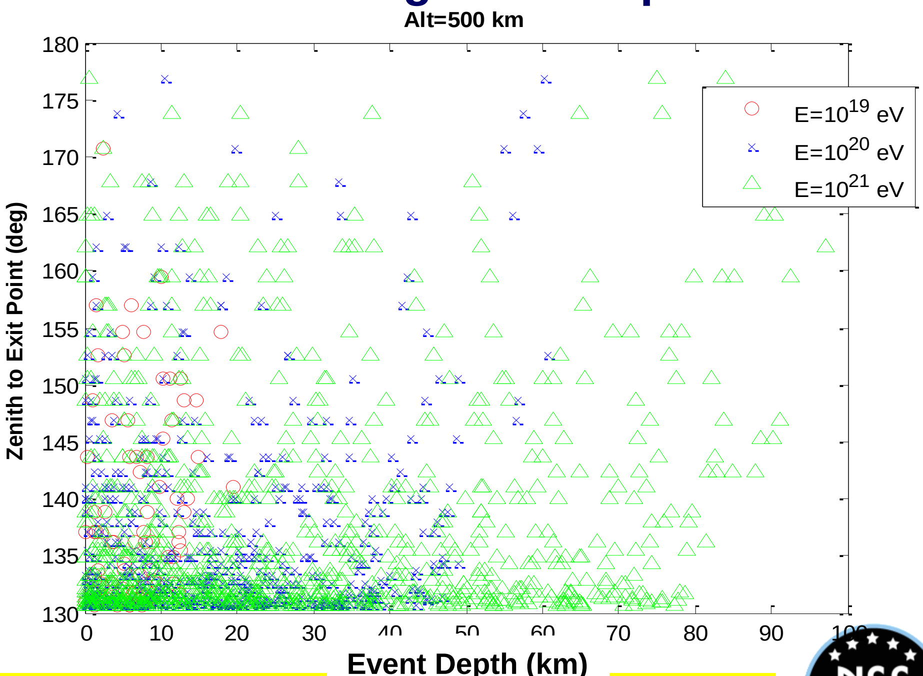
Zenith Angle Distribution

- 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

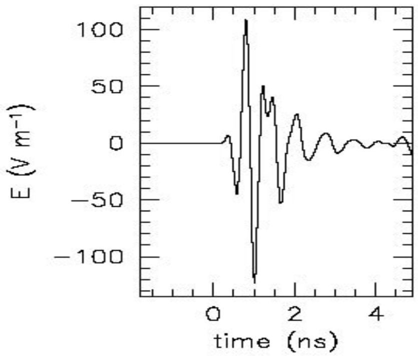
- Event Rate
- Arrival Direction
- Intensity
- Frequency Content
- Direct-Reflected Δt
- Polarization
- Phase?
- Cerenkov Cone?

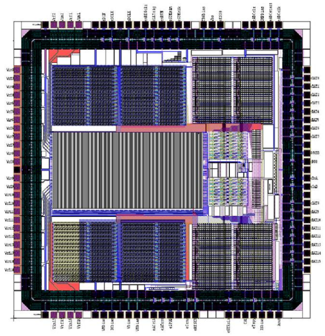
Complicated deconvolution/inverse…

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)
  - Mass ~ 1 kg per antenna
- Power frugal triggering and digitization schemes possible (Switched Capacitor Arrays)
- Data volume is easily within outer planetary mission constraints





Next Steps

- **Simulation Improvements**
  - Greater number of events
  - Ice impurities and temperature models, discontinuities, surface roughness
  - Multi-antenna triggering, off-axis sensitivity, array optimization
  - Uncertainties in neutrino source spectrum
  - Modify for Enceladus and other ice moons, including local water inclusions
  - Detect both direct pulse and reflected pulse from water-ice interface
  - Frequency content of pulses: Attenuation lengths shorter at higher freq's, so events from greater depths should have less high frequency content
  - Backgrounds: *cosmic rays*, thermal from ice, burst and thermal from Jupiter, Galactic RF emission, and Solar burst emission
  - Plan: Adapt existing ICEMC Askaryan Monte Carlo Simulation to PRIDE. Analyze effects not modeled so far. (KU, OSU, APL)
- **Hardware Prototype Development**
  - Develop specialized digitization approaches (UCI)
    - Investigate SCA power requirements, radiation hardness, possible alternatives
  - Develop and test optimized antenna prototype (APL/UCI)

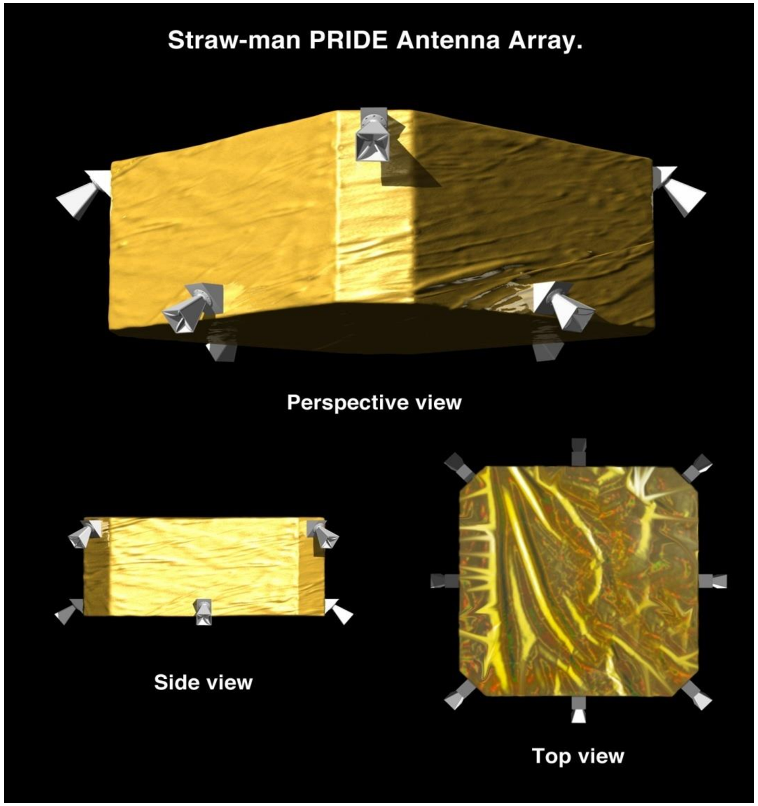
Plans, Next Steps

- **NIAC (NASA Innovative Advanced Concepts) Phase 1 Proposal for 2014-2015 successful!**
  - **Focus on simulation development and Enceladus investigation**
  - **Address simulation questions to strengthen 2014 PICASSO or 2015 NIAC Phase 2 proposal**

- **Next: submit proposal to 2014 NASA PICASSO (Planetary Instrument Concepts for the Advancement of Solar System Observations) Program and/or 2015 NIAC Phase 2 Program**
  - **Goal: Advance TRL from ~2 to 4 over 3 years**
  - **Include both simulation and hardware development**
  - **2013 PICASSO proposal not funded.**
    - **Major reviewer comment: Askaryan EHE neutrinos not yet observed in terrestrial experiments.**
    - **Conclusion: you all need to work harder! (Just kidding… ☺)**

Conclusions

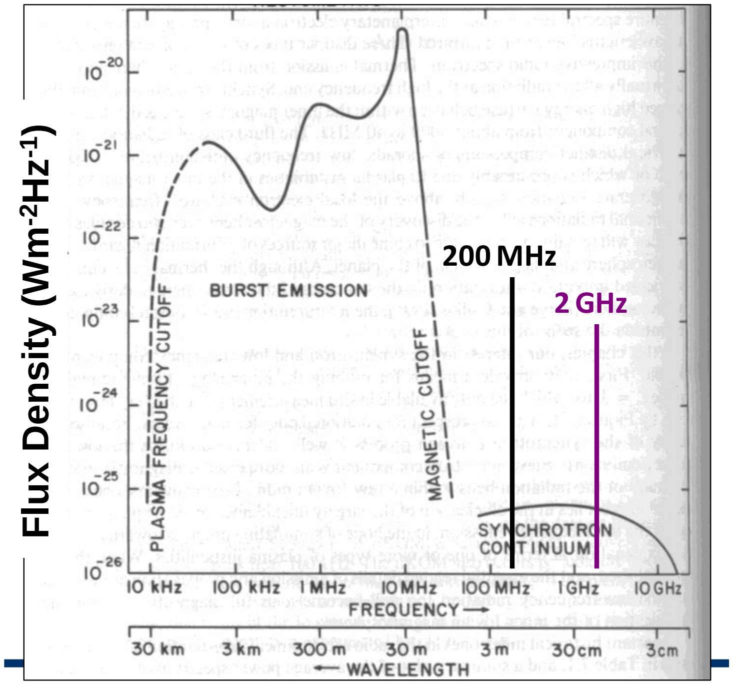
- PRIDE began as an seemingly unlikely concept, but at this time it appears that it may be feasible
- Calculations show that there should be a strong detectable signal and that it can be used to resolve ice shell depth
- We have made a rough instrument design and demonstrated compatibility with an outer 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
  - 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?)

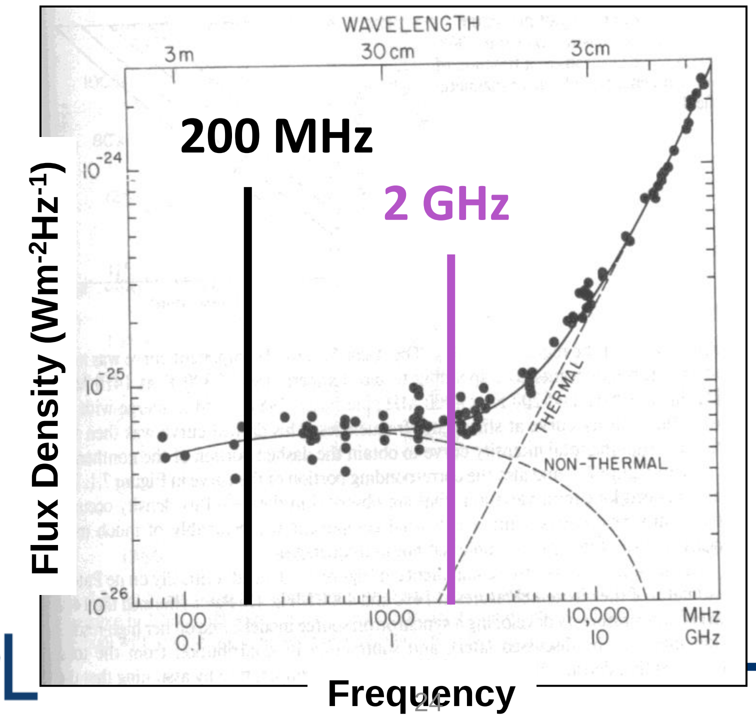


BACKUPS

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





Background: Cosmic Rays

- ANITA detections to date may consist of cosmic rays
- How will cosmic ray events affect PRIDE?
- **Major difference in PRIDE scenario:** Extremely tenuous atmospheres = events impact upon surface, not in atmosphere
  - No separation of shower particles in atmosphere by B field, no horizontal polarization
  - CR interactions always within a few meters of surface, while neutrinos interact throughout ice
  - Statistical distribution of CR and ν locations differ. UHECRs would be seen mostly at lower nadir angle w.r.t. satellite while neutrinos come more from the horizon.
  - Direct Cerenkov emission should not escape due to TIR, but some will due to finite width of Cerenkov cone
  - Reflected Cerenkov emission can escape, so direct-reflected time difference can indicate ice thickness for thin enough ice sheets
  - Different pulse shapes: CRs are dominated by hadronic interactions, almost no influence from the LPM and no preferential absorption of higher frequencies due to shallow depth

- **Bottom Lines:**
  - Possibilities for separating CR from neutrino events, but much work and understanding to do
  - CR's could potentially provide better measurement for shallow ice sheets (via reflections from bottom) while neutrinos provide better measurements for deep oceans

Signal to Noise

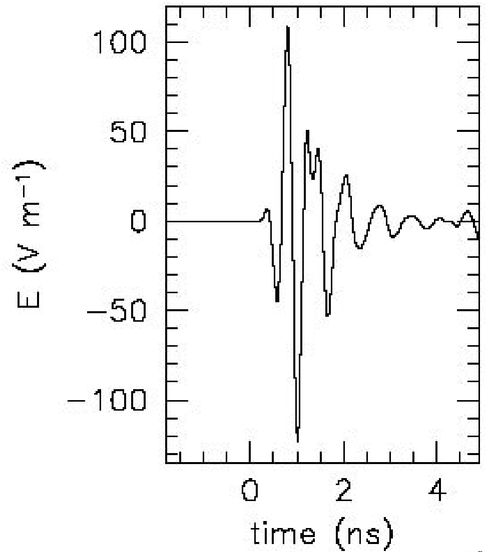
- **Signal: Simple parametric calculation**
  - Neutrino of energy E_n generates a cascade of energy $E_c = yE_n$, where <y> = 0.22 (empirical result)
  - Cascade generates a number of secondary e-/e+: $N_{e+e-} \sim 10^9 (E_c/10^{18}\ \text{eV})$.
  - Excess of negative charge generated: $N_{ex} = 0.2\ N_{e+e-}$
  - 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 = $W_{tot}/(0.36\ \text{sr}) = 8 \times 10^{-8}\ \text{J sr}^{-1}$ 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: $1\ \text{Jy} = 10^{-26}\ \text{W m}^{-2}\ \text{Hz}^{-1}$)
- **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: $kT/A \sim 5.5\times10^5$ Jy

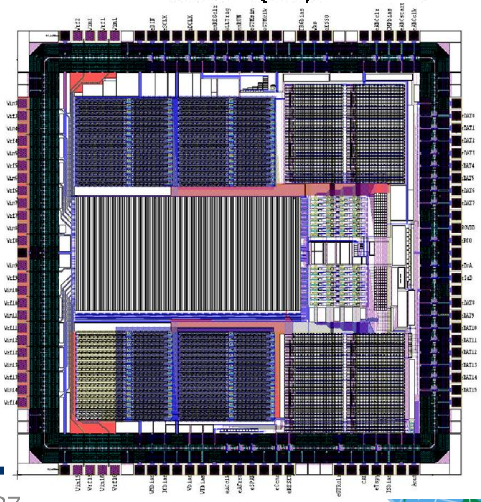
SNR ~ $10^*(E_\nu/10^{19}\ \text{eV})^2$ for small (.25 m^2) antenna at 400 km

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

Typical time domain Askaryan pulse in ice

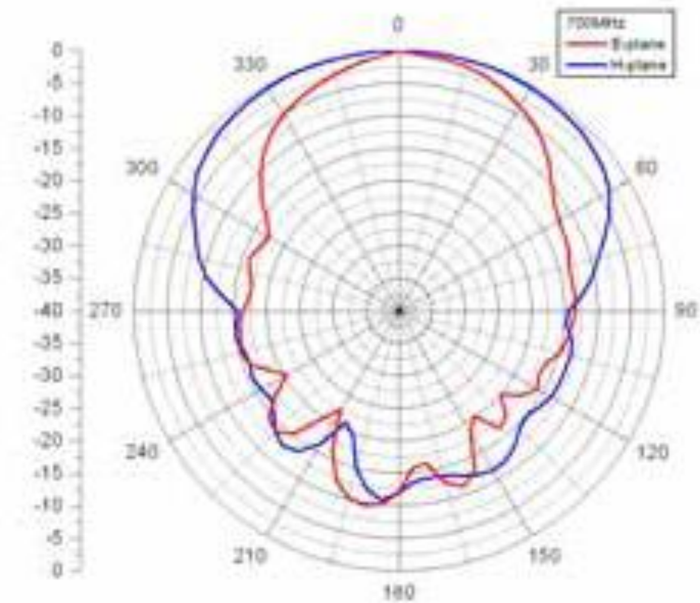




Low power fast digitization solutions exist

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



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