What I would like to know about ice to detect neutrinos

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with thanks to Dave Besson and many others

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• Detecting neutrinos & ice

- zone of visibility (refraction)
- retain signal (attenuation)
- reconstruction
- Ice properties
 - n(z)
 - λ
 - ray optics?
 - birefringence
 - scattering

- RICE, ANITA, ARA, ARIANNA
- Askaryan mechanism
 - neutrino \Rightarrow cascade (spark) \Rightarrow "radio Cerenkov"
 - radio propagates to detector
 - assume ray optics
 - w/attenuation
 - detect event
 - reconstruct using timing, spectrum, polarization

EeV neutrino detection with RICE



ANITA: Overview

ANITA will seek the origin of the *highest* energy particles in the universe, by turning the continent of Antarctica into an enormous Neutrino Telescope







ARIANNA – Hexagonal Radio Array (7 sta)





Askaryan Radio Array (South Pole)



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ARA station







- Analysis assumes H,V and n(z)
- Valid ?
 - two polarizations: mixing, bi-refringence
 - scattering: volumetric, layers
 - boundary effects: surface, channels
 - Location and direction
 - (x,y) z
 - zenith, azimuth

- Passive
 - impurities (attenuation)
 - crystal fabric (birefringence)
- Active
 - detailed timing (ray optics + n(z))
 - detailed amplitudes (ray optics + $\lambda(z)$)
 - H,V (birefringence)
 - messages from the shadow zone (scattering)

- Setup
- Observation of pulses from (3.6, -1.4) km
- Ray optics
 - two paths
 - timing consistent with n(z)
- Ray optics
 - birefringence
 - scattering

Deep pulsers: layout









• Hilbert envelope of cross-correlation of snip.





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Improved reconstruction with two rays

- "Stereo" view:
 - Two eyes vs pupil size
 - Some degeneracy r, θ



- Attenuation model for ANITA
 - temp, impurities
 - impurities not well sampled at depth
 - climate
 - SPICE can help
 - impurity data
 - high quality attenuation data

- Pan-Antarctic model (Javaid: PhD thesis)
 - Follows Fujita, MacGregor
 - Conductivity due to defects
 - thermal, ionic impurities
 - 4D ice model (Fastook)
 - Interpolation of Antarctic impurity data





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Attenuation Results with kriging(Full path)





Legrand Magenesii '97

Impurity vs depth (climate considerations)



- Pan-Antarctic model developed for ANITA
- Makes predictions for SP
 - based on incomplete data
- SPICE core can supply impurity data
 - improve model
- Controlled pulsing from SPICE \Rightarrow ARA
 - test model
- Useful for ARA and ANITA

•
$$n(z) = f(\rho(z))$$

Gow, EMT







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•
$$n(z) = f(\rho(z))$$

RICE



Gow, EMT



Patterson (Physics of Glaciers)





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Does it matter? Shadow Zone for z = 200m, model: 7ρ : simple Shadow Zone for z = 200m, model: 7ρ : Gow 100 100 Nominal n simple n p - Gow 0 0 ∄_ -100 ∄_ -100 -200-200-300 -300 0 200 400 600 800 1000 1200 1400 500 1000 1500 0 r (m) r (m) Shadow Zone for z = 200m, model: 5p: Gow Shadow Zone for z = 200m, model: 6ρ : Gow 100 100 n-11+2 p-6000 p-Gow 0 ∄_ -100 ∄_ -100 -200-200-300 -300 0 500 1000 1500 200 400 600 800 1000 1200 1400 0 r (m) r (m)

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Is it flat ?

31,074

VAN DER VEEN ET AL.: COMPARING SOUTH POLE ACCUMULATION RECORDS



Figure 8. Topographic map of the South Pole region, based on Global Positioning System surveys (radial lines) and barometry (two circular traverses at 10 and 20 km from South Pole). Contour interval is 4 m.

- Birefringence
 - Deep pulser shows Hpol ... but it's early by 30 ns
 - Consistent with crystal orientation
 - What can SPICE do ?
 - Measure COF
 - Provide rich data set
- Scattering



Birefringence: Hpol/Vpol snips



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Birefringence & crystal fabric



scattering & horizontal propagation

- Evidence from RICE, ARIANNA for horizontal propagation in the firn
- e.g. "bouncing", trapping layers, detailed balance?



scattering & horizontal propagation

- ARA Deep pulses
 - Refracted pulse has early activity
 - evidence for scattering in the firn?



SPICE hole pulser (movie?)



Detail timing near the shadow edge



Summary

- Radio detection of neutrinos in-ice can
 - extend the high energy frontier
 - at modest cost
- Need good ice-models
 - n(z), attenuation
 - ray optics: birefringence, scattering
- SPICE core
 - impurities
 - crystal orientation
 - detailed timing tests
 - HV
 - probe shadow region