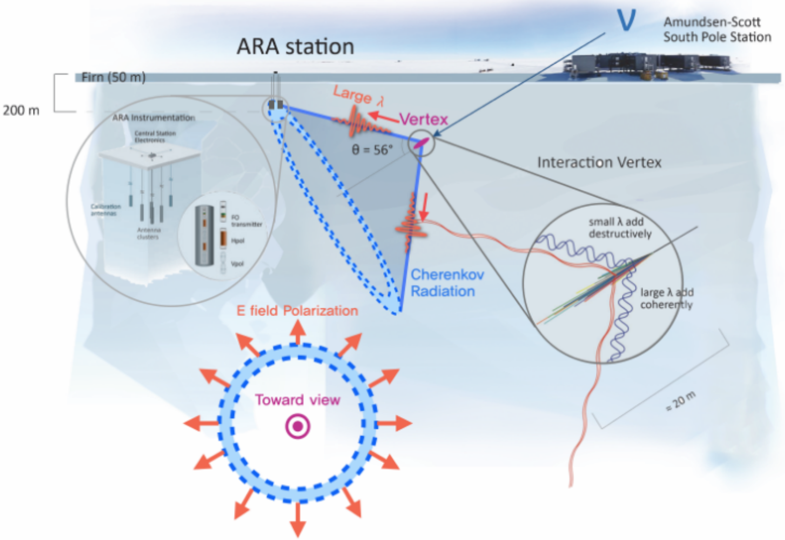
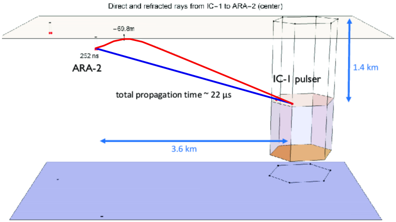
Disclaimer

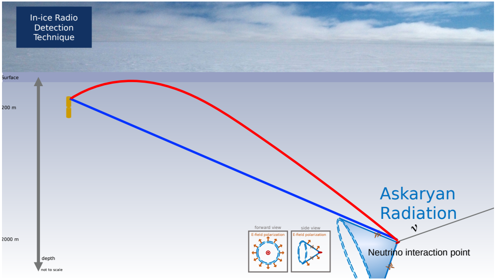
- I have only a cursory knowledge of glaciology-there are more informed/qualified people to give this talk (presented here is my own personal take)
    - Emphasis on symbiosis: neutrino detection via measurement of RF signal produced in-ice$\leftrightarrow$(radio)glaciology
    - What do we know and what remains unexplained?
    - How do we optimize science from IceCube-Gen2 radio (ICG2R)?
- Program: For signal $\vec{E}_{\vec{k}}$, what is $\epsilon'(\vec{k}, z, \omega)$ ($\mathbf{n}$(z)), $\epsilon''(\vec{k}, z, \omega)$ (L_α)?
    - Assume ICG2R design comprising 200 radio receiver stations deployed over 500 km^2 (https://arxiv.org/pdf/2008.04323)
    - Station: 8 surface channels (4 LPDA + 4 near-surface Phased Array),
        - https://arxiv.org/pdf/1809.04573
    - 16 channels (8 VPol/8 HPol) at vertices of 20m x 20m x 20m cuboid,
        - 180-200 m deep, 25-cm caliber BIG RAID-drilled dry holes (J. Rix).

Decoding ν direction from Cherenkov-cone

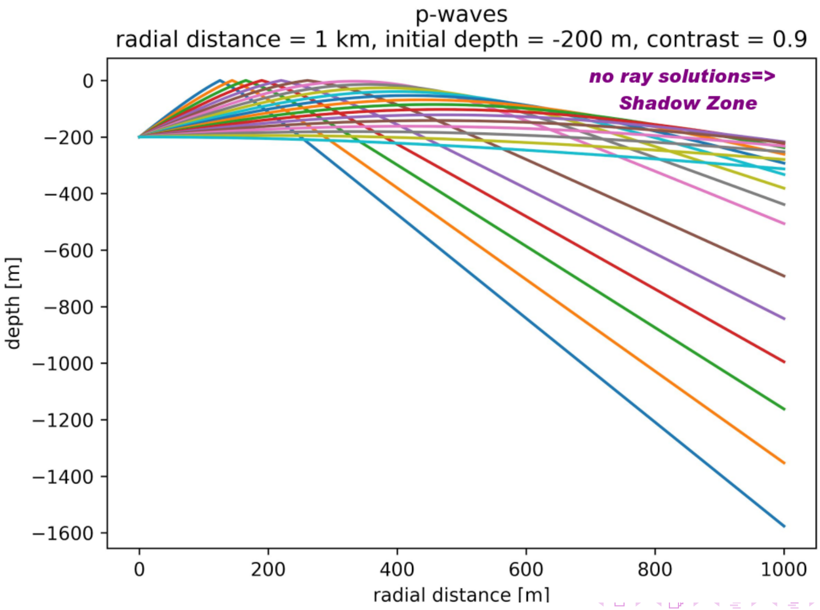


Ray Bending (dn/dz)⇒D and R solns (mirage effect)





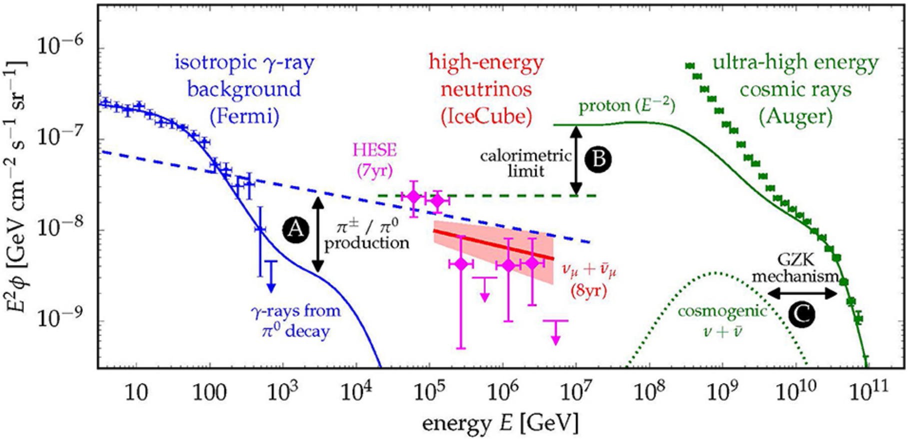
Ray Bending⇒shadowing (N. Harty)



Science drivers: E_ν distribution and sources

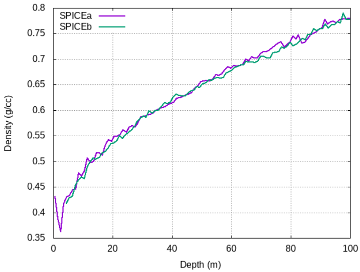
- What is the neutrino energy spectrum from 10^{16-19} electron Volts?
  - Does the spectrum follow the power law measured by IceCube? $dN/dE \sim E^{-2.2}$
- What are the specific sources of these high-energy neutrinos?
  - Low end of sensitive energy range:
    - Are there sources like Blazar TXS 056+0506 indicated by IceCube optical?

Neutrino Spectrum (Halzen/Ahlers compilation)



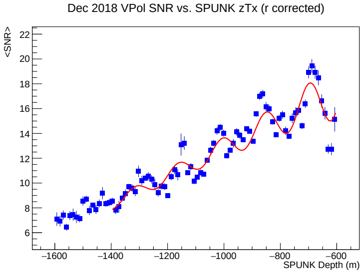
Neutrino/CR Science↔Glaciology

- E_ν <50 PeV, ice volume over which neutrinos detectable ($V^{\nu}_{eff}(E_\nu)$) limited by 'shadowing', determined by n(z)⇔does n(z)=1+0.86$\rho(z)$?
  - ⇒measure $\rho(z)$ from BIG RAID chips
  - n(z) input for bedrock mapping by aerial surveys (BAS, CReSIS, e.g.)
- To infer Cherenkov cone, need distance to interaction (from $\delta_t(Direct, Refracted)$)
  - Currently, ∼10% errors, limited by $\delta(n(z))$ (2.5% accessible)
  - How do fluctuations in $\rho(z)$ (indicated by SPICE core data, e.g., FDTD simulations) modify $V^{\nu}_{eff}(E_\nu)$ and limit ν pointing?



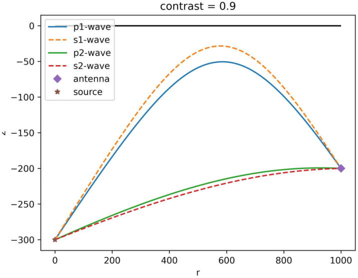
Unexplained stuff

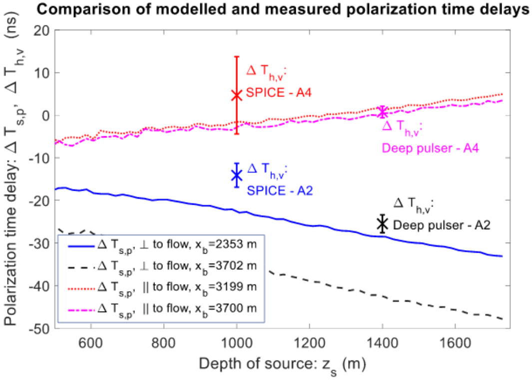
- Why do both ARIANNA (surface Rx) and ARA (z∼-180 m) see oscillatory behavior in $A_{Rx}(z_{Tx})$?
- What is the source of the near-surface RICE time 'inversion'?
- Why does a simple birefringence model, bootstrapped from SPICE core grain measurements, work for horizontal propagation, but not for vertical propagation?
- How is it that we observe signals from the 'shadow' zone? (prohibited if n(z) profile smooth)



Biref: n=n($\vec{k}, \hat{E}$); data $n_o - n_e$ ~0.13% (N. Harty)

Arrival time difference (VPol-HPol) differs for along-flow vs. flow-perp





Neutrino/CR Science↔Glaciology

- For E_ν >100 PeV ("GZK"-neutrinos), V^ν_{eff} limited by L_α⇔What is temperature profile dT/dz (global thermal modeling) and impurity concentrations
  - Joe MacGregor (glaciologist) and Amir Javaid/Mark Stockham (astrophysicists) separately published on same topic.
- For surface radio array component (includes measuring radio signal from down-coming air showers), how does snow accumulation near surface impact antenna response?⇔mass balance modeling
- How do birefringent effects lead to an over-estimate of $V^\nu_{eff}(E_\nu)$?⇔How is the ice fabric changing as a function of depth?

How do all of the above vary over the scale of 500 sq. km?

Calibrating receiver antennas

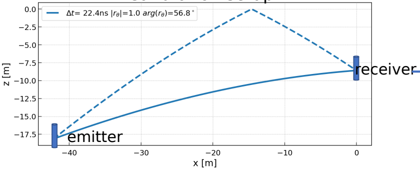
- Want a full-circuit gain calibration using calibrated Tx over range of $(\phi_{Tx\rightarrow Rx}, \theta_{Tx\rightarrow Rx})$
- To get neutrino incidence angles, need to precisely measure relative timing/antenna positions
  - Need precision measurements of cable delays at < 100ps
  - Need precision measurements of group delays as f(θ, ϕ)
    - Pre-deployment in-lab as f(temperature)
    - Post-deployment *in situ* with at least subset of antennas
- 10 cm/yr snow accumulation will change n(z)$\Rightarrow$re-calibrate surface antennas year-to-year
  - Can use ARIANNA trick to precisely measure accumulation if equip w/ near-surface Tx

arXiv:1909.02677

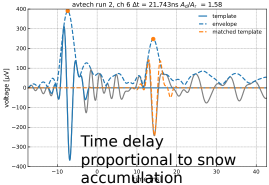
Measurement of firn properties

- Monitoring of snow accumulation and n(z) of the firn required for neutrino event reconstruction

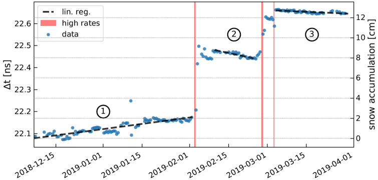
Calibration setup



Direct and reflected signal pulse



Snow accumulation at Moore's Bay, ~1mm precision



- Setup can be extended to also measure the index-of-refraction profile in the upper ~20m
  - n(z) = 1.78 – A * exp(-z * B) -> parameters A+B can be determined
- Future detectors might provide such measurements over >100km² at South Pole, Greenland and Moore's Bay, is this of interest?

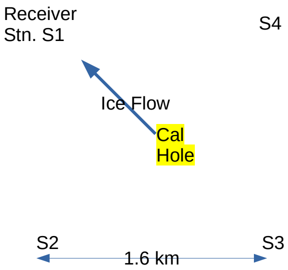
Cal Pulser→Cal Hole+Tower

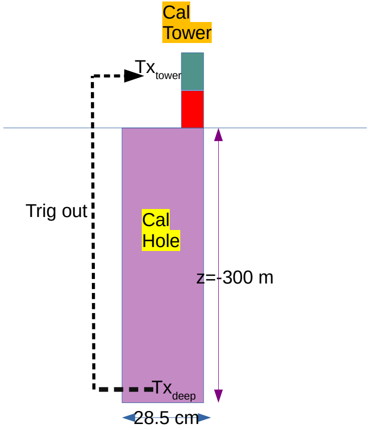
- Propose that, for every N (=32? =16?) stations, drill one dedicated 'calibration' hole at inter-station grid center.
- zTx(z=-100m)→zRx(z=-200m) horizon at ∼1 km.
  - For 1.6 km station spacing on square grid, need to get down to ∼300 m to safely illuminate nearest-neighbors from a centrally-located Tx calibration hole
- Propose most (3/4?) cal holes filled with 'permanent' instrumentation
  - DS: Possibly including two Tx separated by multi-meter scales
- Tx operated in either pulsed, tone (of variable duration), or CW mode (autonomously-powered)
  - L_{atten} not possible via near/far measurement, will require absolute dead-reckoned P_{Rx}/P_{Tx}
  - Remaining holes left empty for, e.g., periodic S11(z_{Rx}) measurements, $V_{Rx}(z_{Tx})$

Station synchronization/averaging⇒Cal Tower

- Need to synchronize DAQ clocks on surface
  - Standard GPS (plus tricks)
    - Current ARA intra-station timing resolution ∼1–2 microseconds
  - ⇒Propose put VPol/HPol Tx atop 4-5 m calibration tower
    - "Segmented tower" to anticipate accumulation?
- For ice properties measurements over long baselines, would like to have waveform-averaging capabilities for low-SNR signals⇒trigger locked to high-SNR surface dipole→in-ice Rx pulses.
- If locked in, possibility of measuring L_{atten} via bottom bounce!
- Can also use a drone (a la' TAROGE-M) to verify $\epsilon(\theta)$, although does not facilitate signal averaging
  - tethered balloon?
  - HiCalX on a cubesat?

Calibration Tower Hole





Summary

I'm sure there's an unprecedented opportunity here; optimizing neutrino science **requires** coordination and input from glaciological community!

"We defy augury...In the readiness is all"