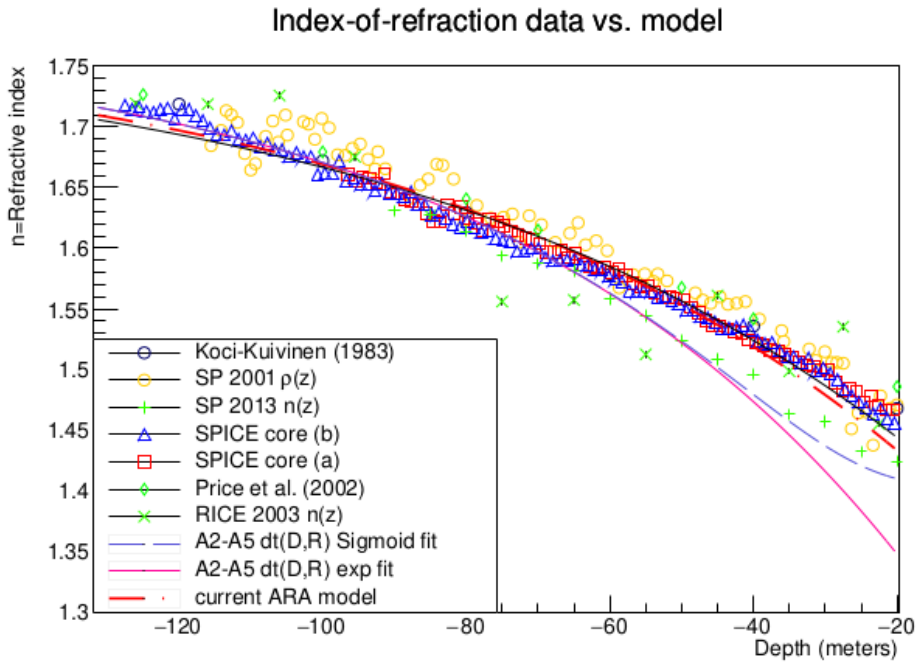
Neutrino Science Context

Three goals:

- Neutrino ID:
  - upcoming RF signal ($\sim$20–25% downcoming R signals)
  - Convincing impulsive signals in receiver channels
- Neutrino astronomy:
  - Pointing into sky: Reconstruction of Cherenkov cone
    - Polarization (H,V projections)
    - Frequency gradient across array
    - range from δ_t(D,R) + δ_t(H-V)
    - θ,ϕ reconstruction
- dN/dE_ν: High statistics sample of events with good range-to-vertex
  - But likely limited by inelasticity uncertainties

Refractive Index Ice Uncertainties

- Re(ϵ)$\Rightarrow$non-shadowed volume
  - limits E_ν <50 PeV V_{eff}
  - Use ρ(z) as a proxy: n(z)=1+0.86ρ(z)
  - 'Probably reasonable'
- https://arxiv.org/pdf/1908.10689: ARA global fit to SPICE core δ_t(D,R) gives different n(z) results for different stations
  - Rx below 100 m favor n(z)$\sim$A+Bexp(Cz); Rx above 100 m favor 'sigmoid' model with z$\sim$-25 m inflection

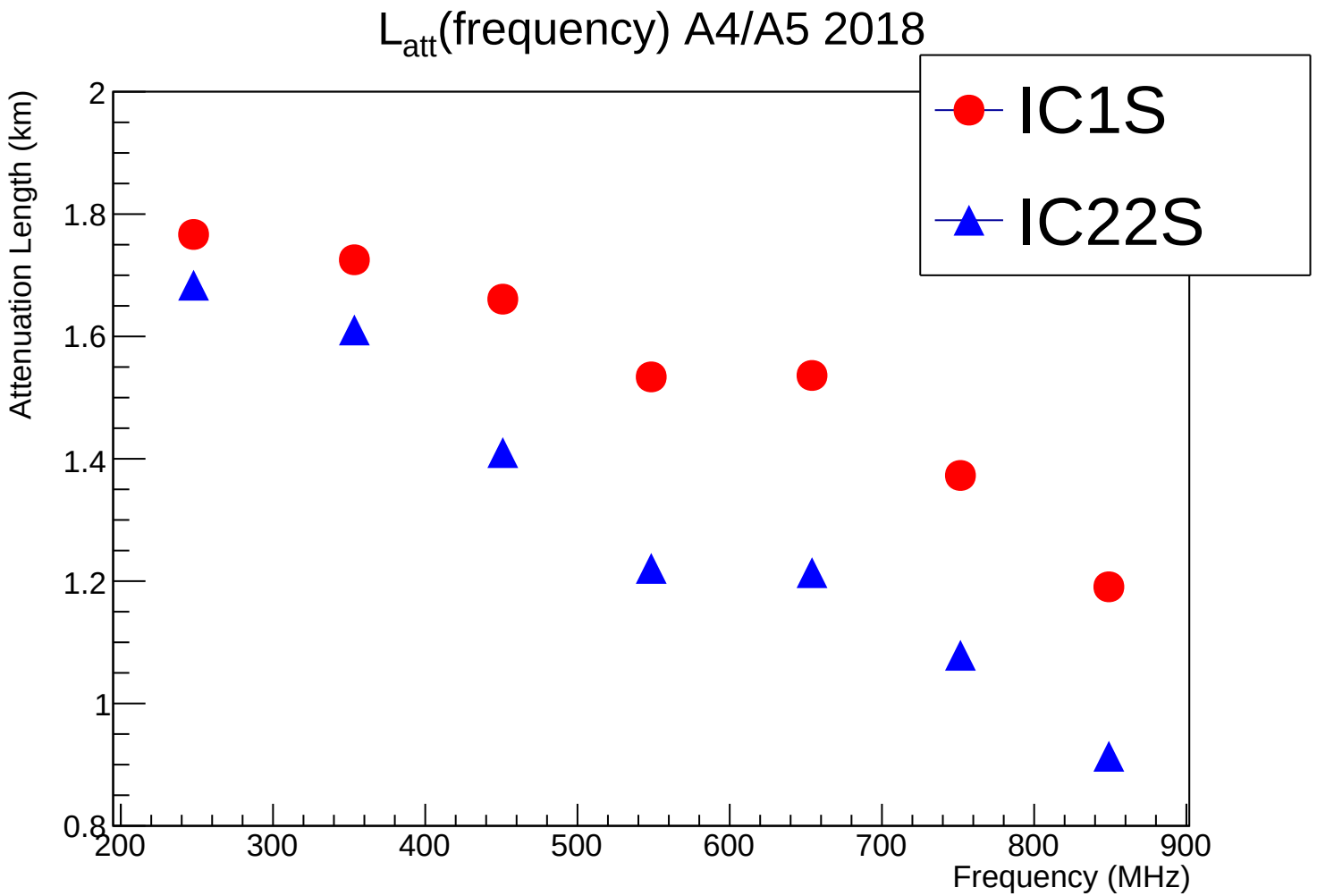


Refractive index future progress

- If load cell can be upgraded, BAS drillers will measure $\rho_{ice}(z)$ for each RNO-G hole
  - targeted precision of 1%
  - Current errors $\sim$4%
  - (will cross-check against density from chips immersed in cooking oil)
- With conductivity(depth) from SPICE core, cross-check RICE internal layer reflection data against models
  - Clear echoes at 6μs, 9μs, 14μs, 17μs, and bedrock (34μs) with travel time precision $\sim$3-4 ns

Attenuation Length uncertainties

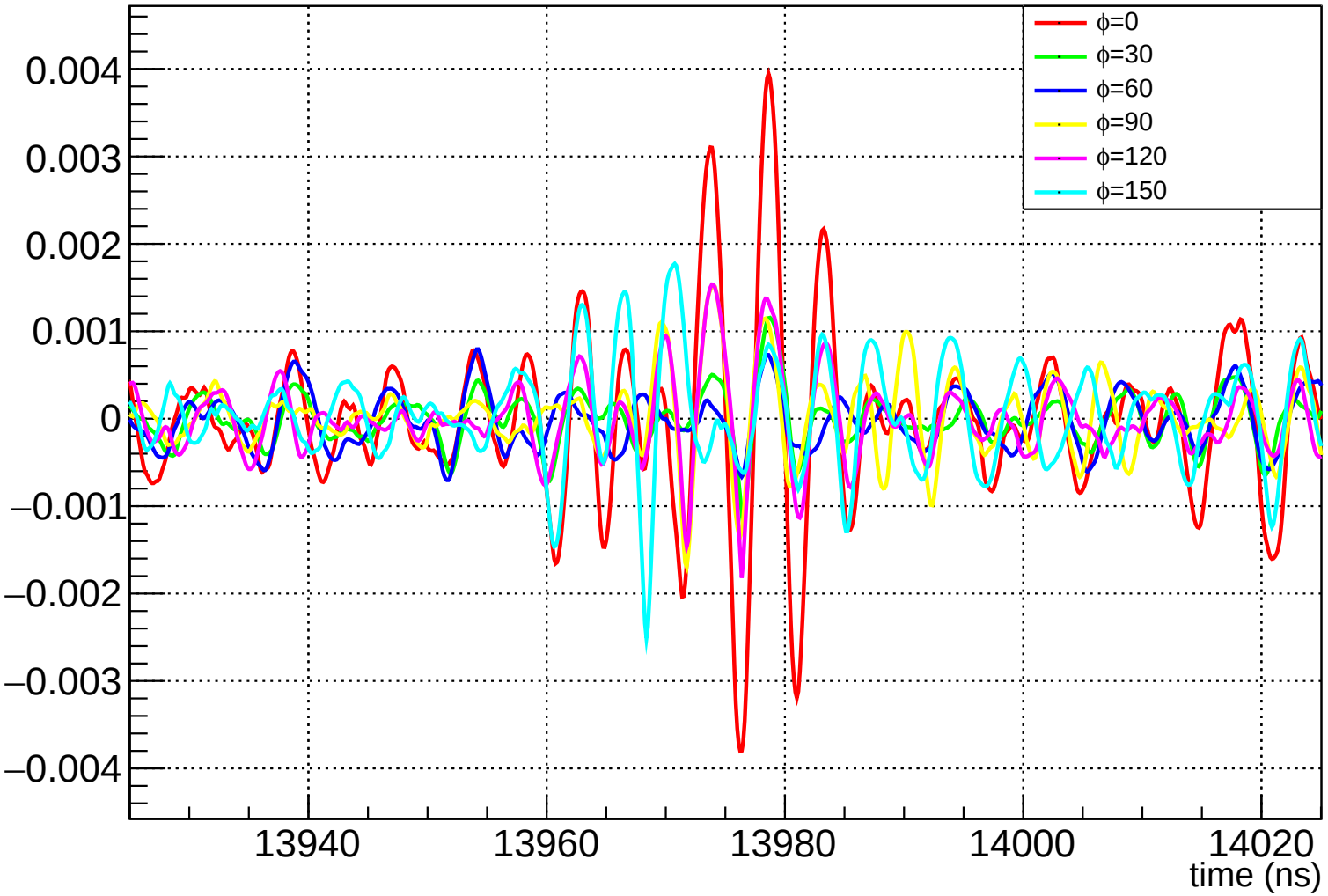
- Dominate V_{eff} estimate at >100 PeV; current precision OK for ν ID
- Uncertainties likely sub-dominant for frequency gradient
- re-measure at RNO-G (although $T_{ice}^{Greenland} > T_{ice}^{SP}$)



Birefringence

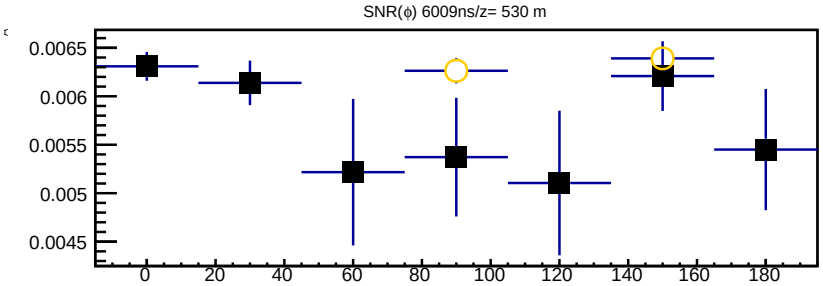
- Polarization vector splits and projects onto birefringence basis
  - In process of being implemented in nuRadioMC
- Model based on SPICE core ice fabric data tested against SPICE core RF propagation
  - ARA gives reasonable agreement for mostly horizontal (δz $\sim$2-5 km) trajectories
- Currently testing Model against vertical propagation geometries
  - ARIANNA SPICE core data (both VPol and HPol signals)
  - ARA Deep Pulser$\rightarrow$testbed data (VPol$\rightarrow$VPol)
  - Archival RICE data: HPol only, varying ϕ (i.e., n1/n2 relative projections)
    - Bedrock Echo reflections
    - Internal Layer reflections

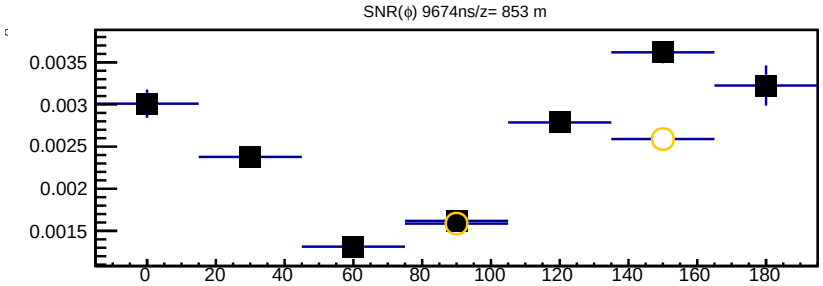
13975 ns echo

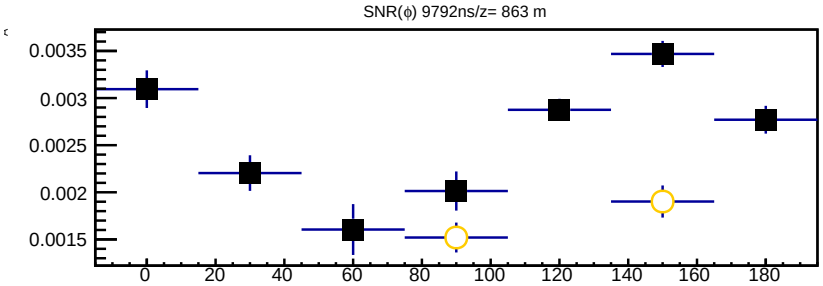


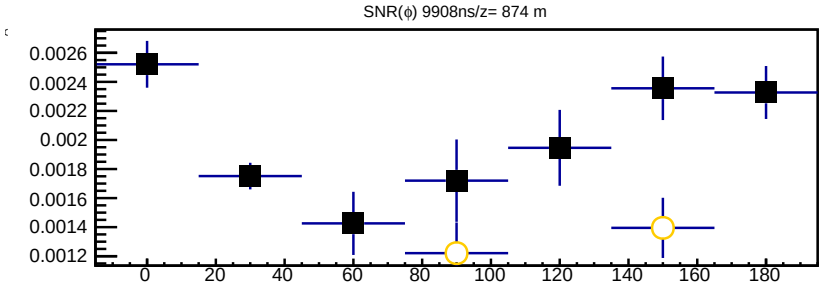
SPICE core ice fabric $(n_2 - n_1) \sim 0.003 \Rightarrow$ expect$\sim$30 ns/100 ns
internal-layer/bedrock asymmetry, vs measurement $<$10 ns/50 ns

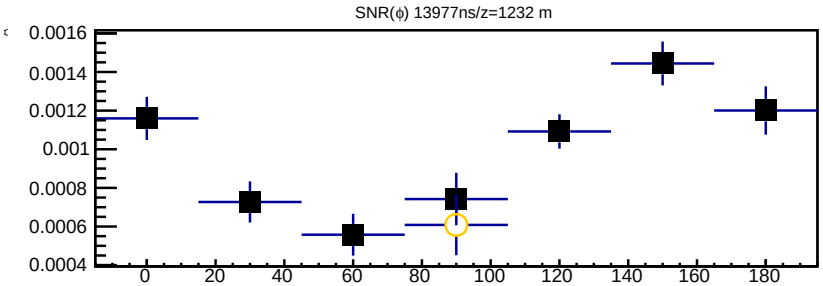
RICE A(ϕ) for various echoes - ice flow at $\sim 60°$

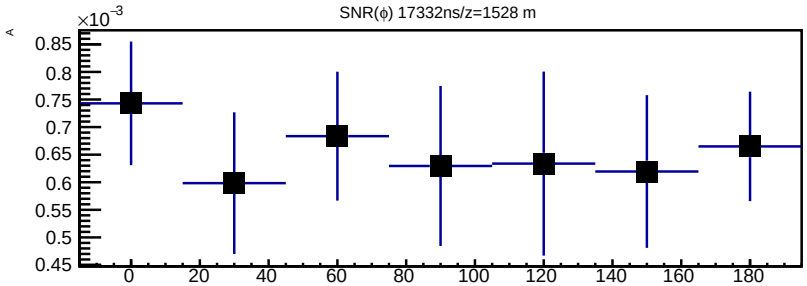


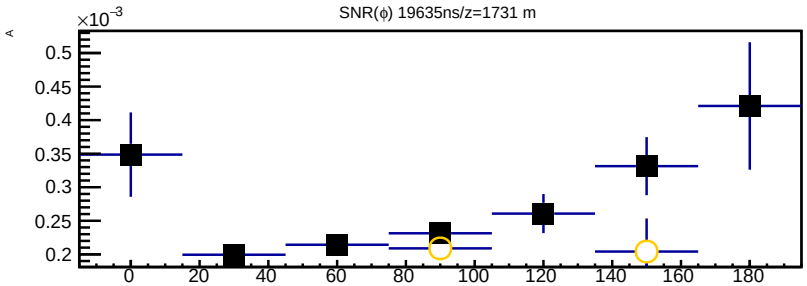










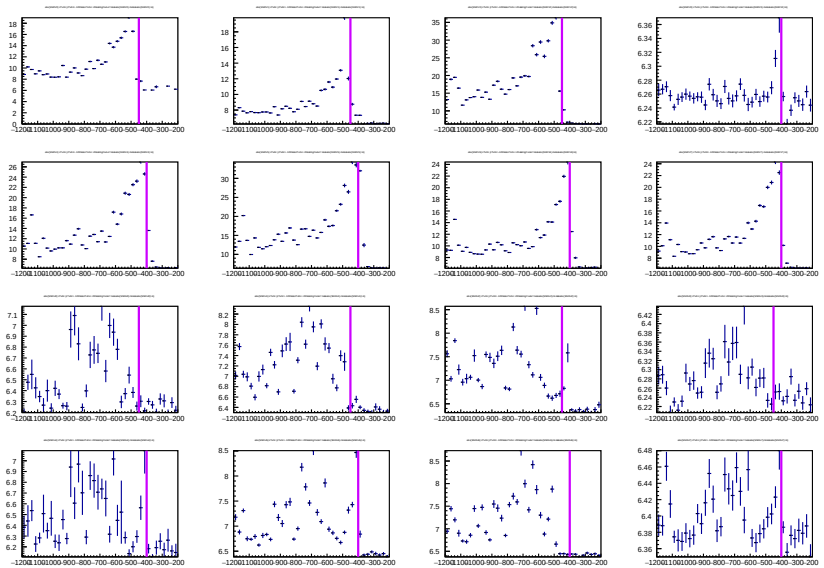


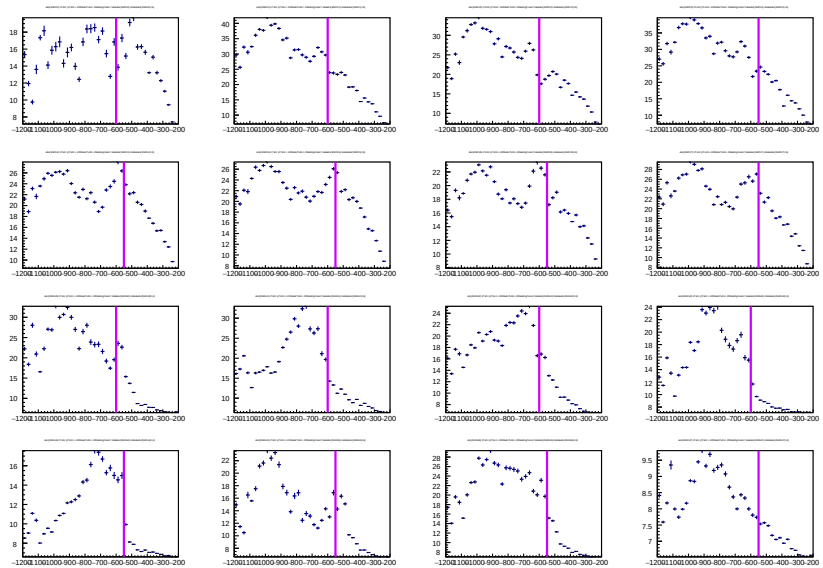
Possibly important things we don't understand

- What is the origin of the shadow zone signals, and what are they telling us about our lack of understanding in the *non-shadowed* region?
- Shadow-zone propagation$\leftrightarrow$incomplete cancellation of Huygens wavelets!
  - Extensive measurements by ARIANNA (Robert Lahmann)
  - Also observed in Greenland data, AND predicted by FDTD simulations (Cosmin, others) and Parabolic Equations (Steven, others) that include density variations.
  - L_{atten} $\sim$500 meters
  - BUT: very irregular signals and large amplitude variations for Tx/Rx variations of order 5 m, at horizontal displacements of 3.4 km.

ARA HPol/VPol power for A3 (left)/A1 (right) as f(z_{Tx}

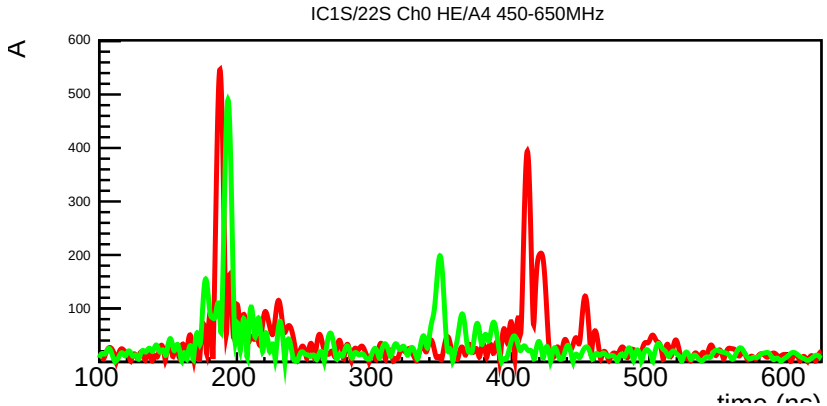
Left: A3 SNR vs. SPICE zTx (zRx:-180→-200 m)
Right: A1 SNR vs. SPICE zTx (zRx:-50→-70 m)

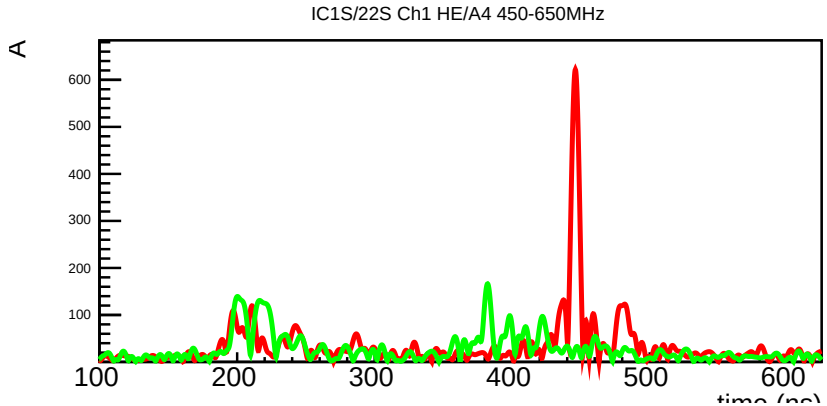


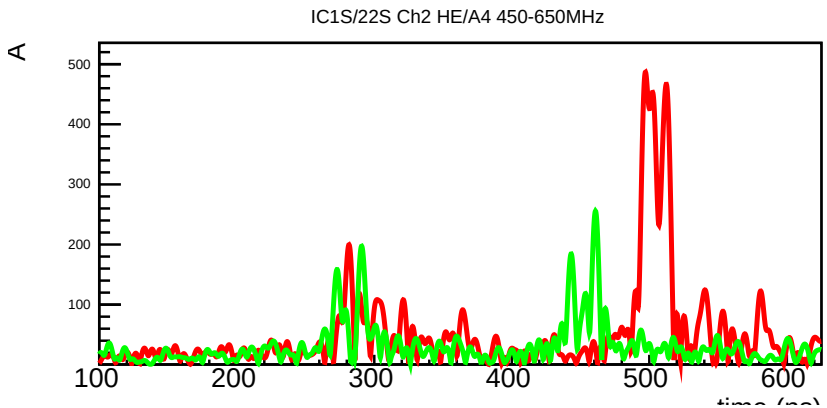


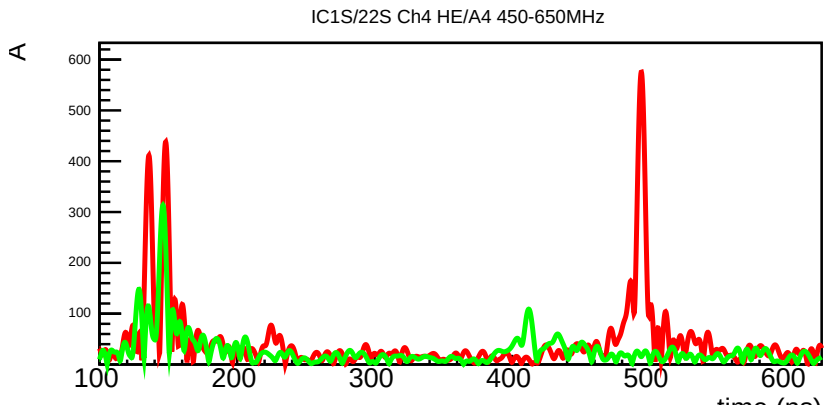
Why does $A_D(\omega)/A_R(\omega)$ vary so much for Rx 20 m separated?

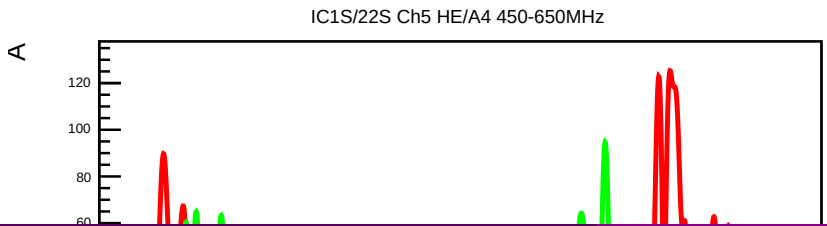
Frequency band 450-650 MHz / A2 SPICE core data

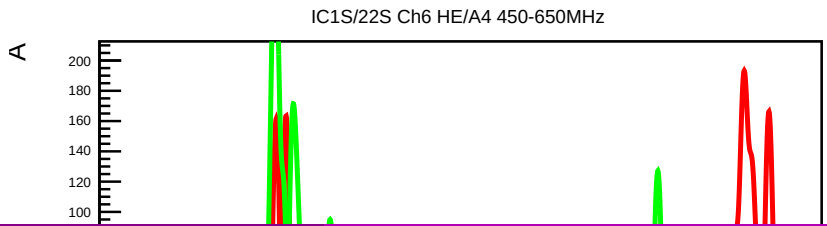












Summary

- We know enough about the ice to do neutrino ID
- To do neutrino astronomy, we need to rachet up our understanding
  - (in my opinion) need to meld something like a fast parabolic solver or FDTD routine into nuradiomc
  - Even then, we will likely not understand the ice on a ray-by-ray basis, but will have to parameterize statistically