

Density fluctuations in the firn and ultra-high energy neutrino detection

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ULB

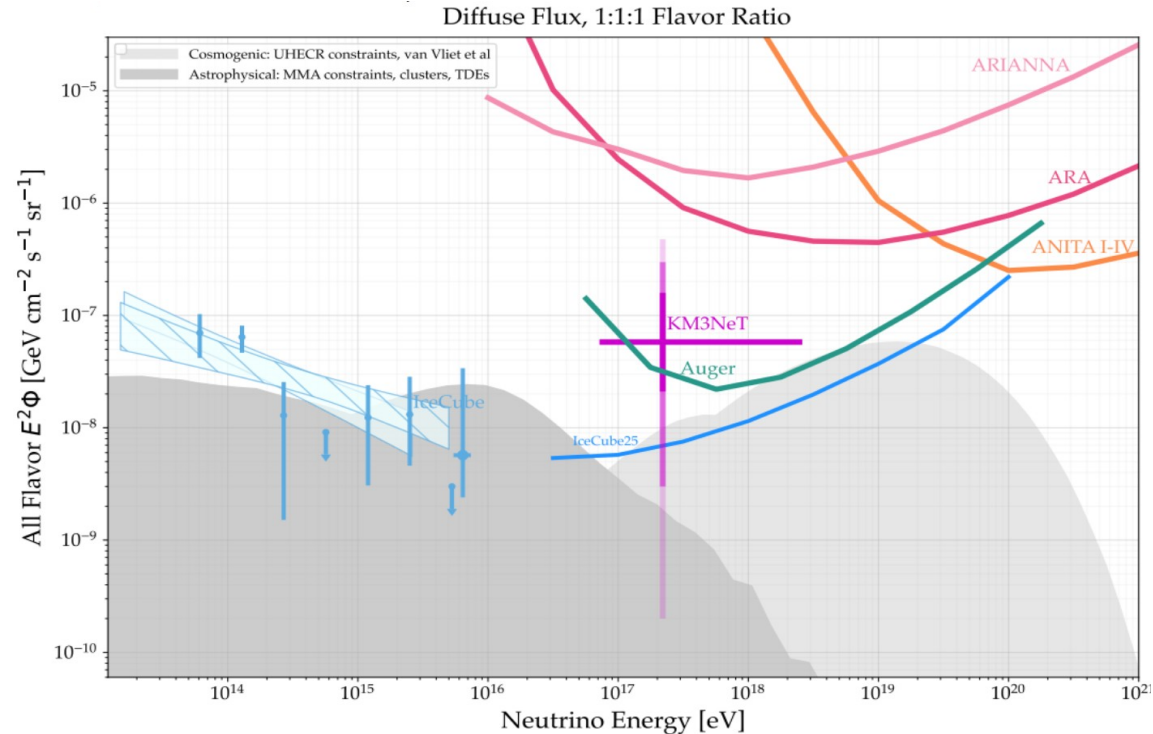
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Ultra High Energy Neutrinos

- UHENs ($E > 10$ PeV) can point to sources of the UHE cosmic rays
- Key to BSM Physics?

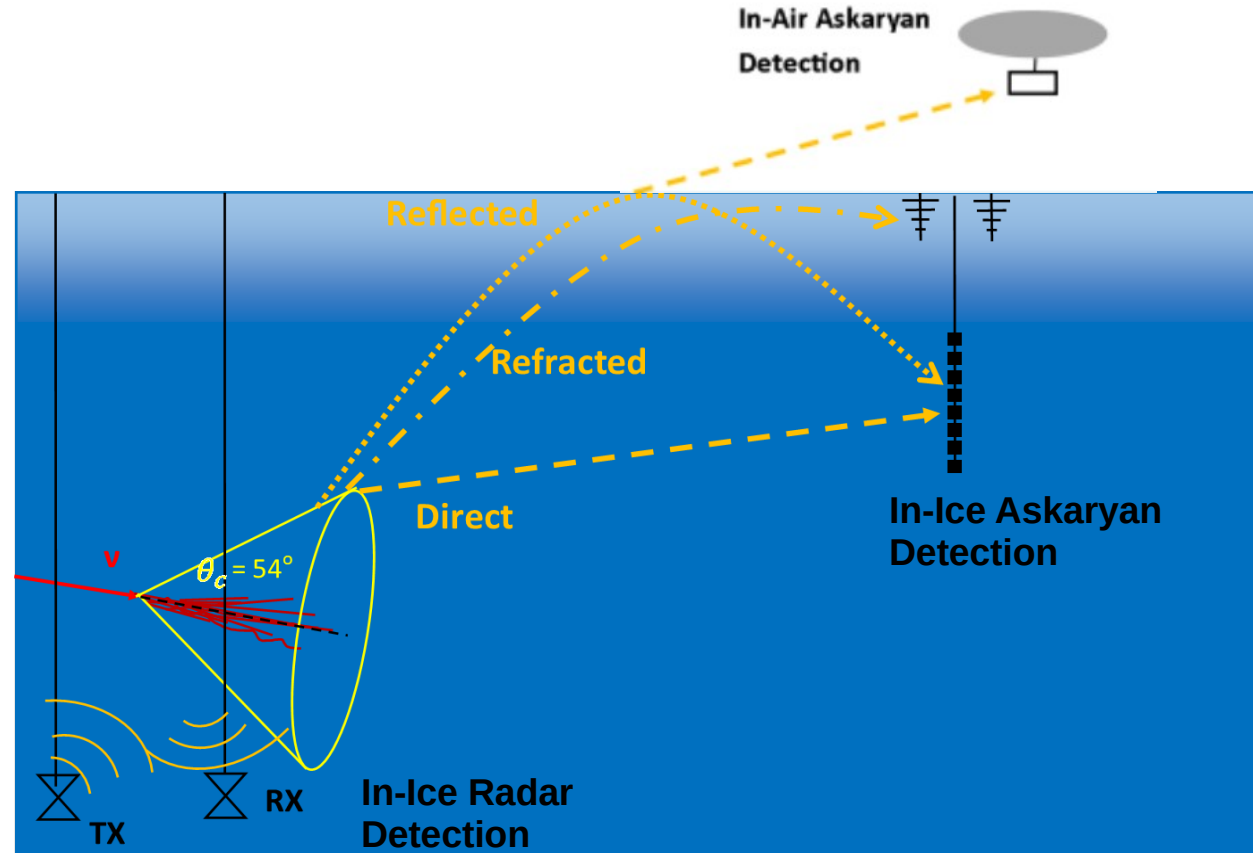
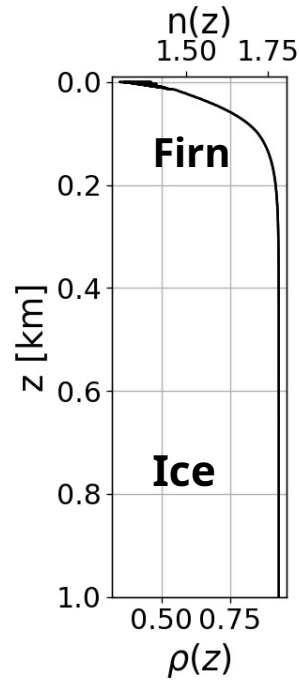
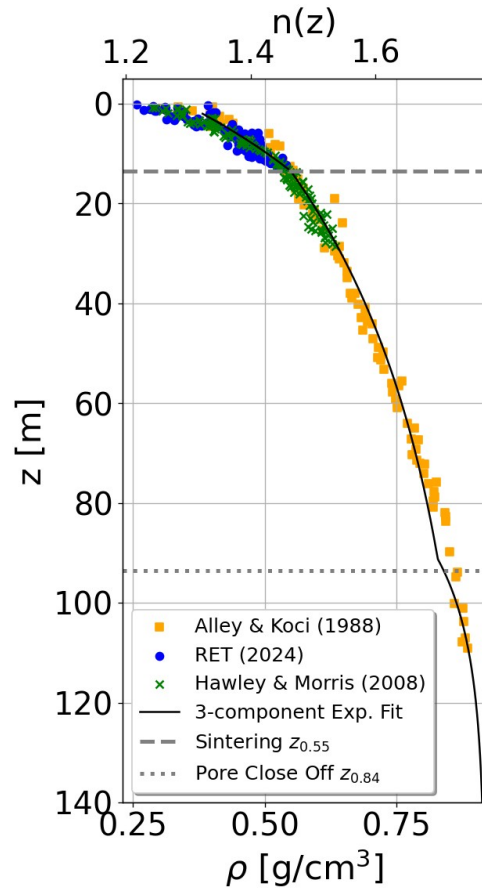
Current picture for UHENs:

- Upper limits < 1 event per km^3 / decade
- KM3NET event – ($\sim 2.9\sigma$ tension)
- Needed detection volumes $\sim 10 \text{ km}^3$
 - expensive for optical-based detectors
 - radio detection paradigm

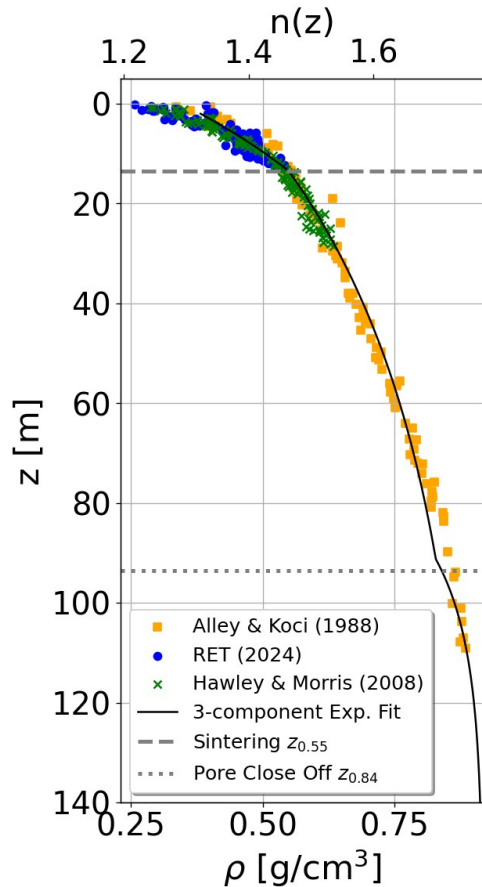


Credit: Snowmass White Paper: arxiv.org/pdf/2203.08096.pdf – Adapted by J.A. Aguilar (TeVPA 2025)

UHEN Detection in Ice



Firn Densification



Snow:
settling and grain growth
 200 kg m^{-3}

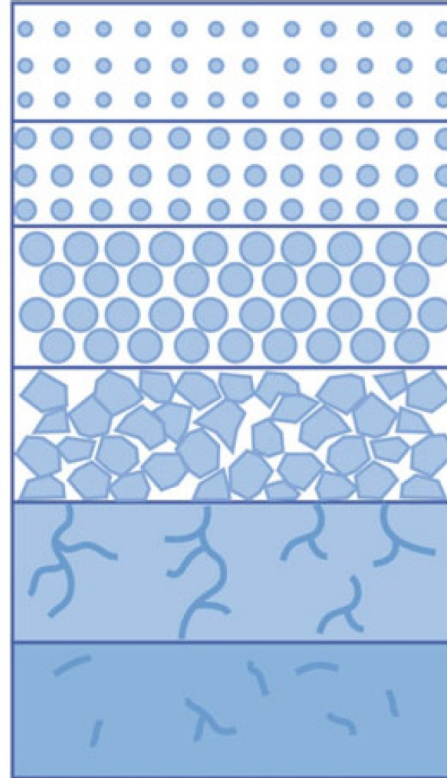
Firn:
settling and grain growth
 400 kg m^{-3}

Firn:
settling and grain growth
 550 kg m^{-3}

Sintering
 800 kg m^{-3}

Pore close-off
 830 kg m^{-3}

Glacier ice
 900 kg m^{-3}



Buizert & Helsen, *Glaciers and Ice Sheets in the Climate System*, Chapter 11 (Springer)

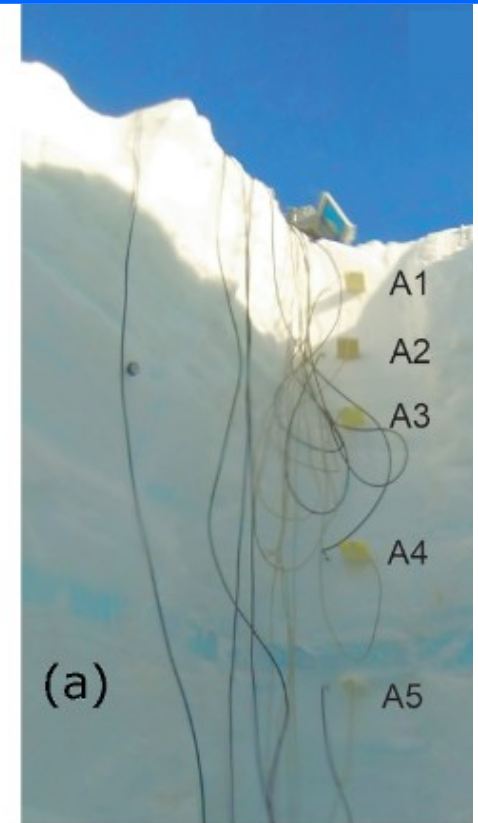
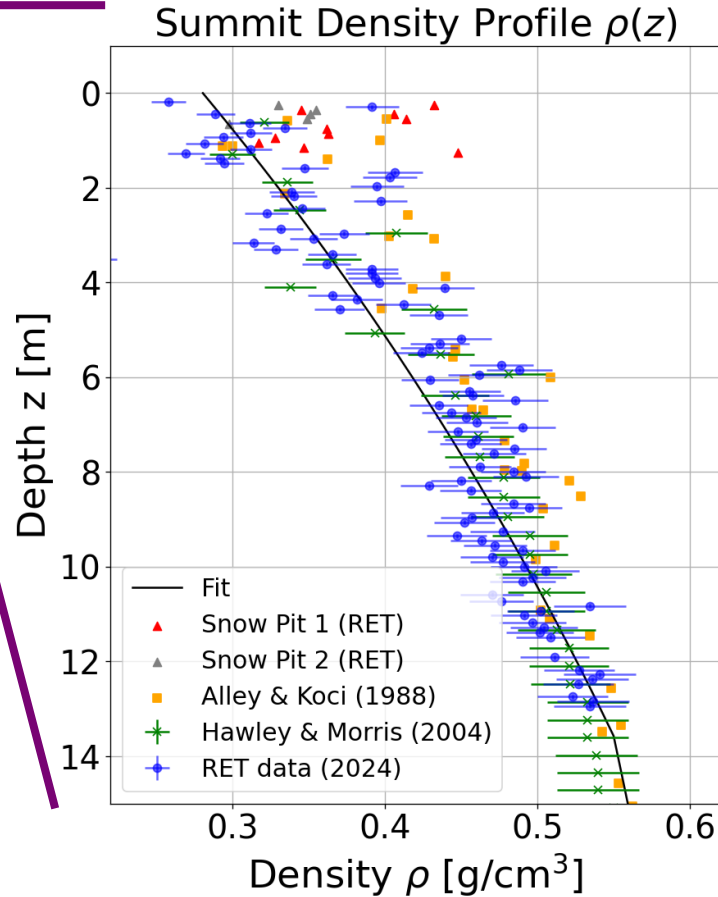
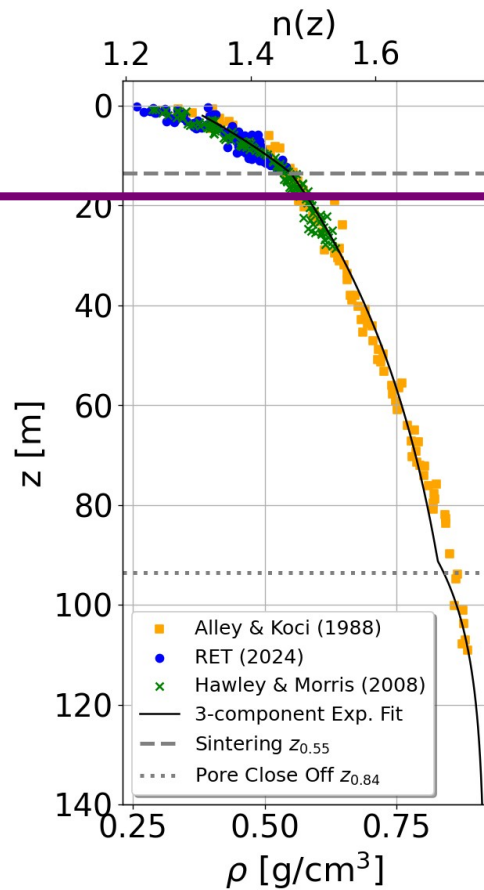
Empirical models of density:

$$\rho(z) = \rho_i + (\rho_s - \rho_i) e^{-kz}$$

Densification rate k

- Models different physical processes (settling and sintering)
- Temperature dependent

Evolution of the firn



Ice layers in glacial firn at the field site Dye-2 (Site-A) Greenland summer of 2016 (Samimi et al., 2020):

Firn Evolution and Neutrino Detection

How does the time evolution of firn affect neutrino detection with radio?

Simulation Study: Summit, Greenland as a test case (RNO-G and RET-CR)

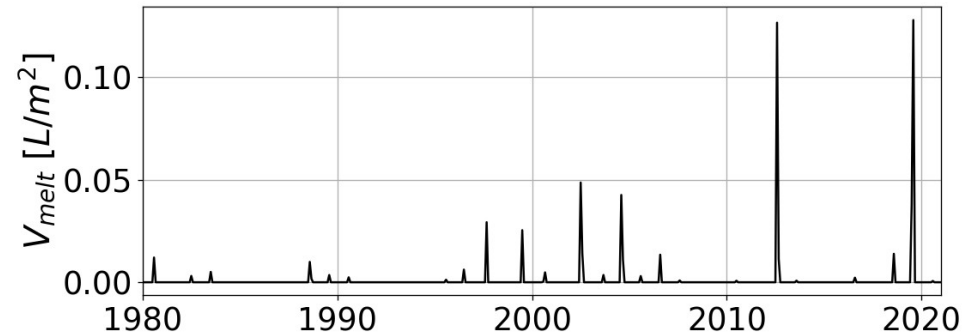
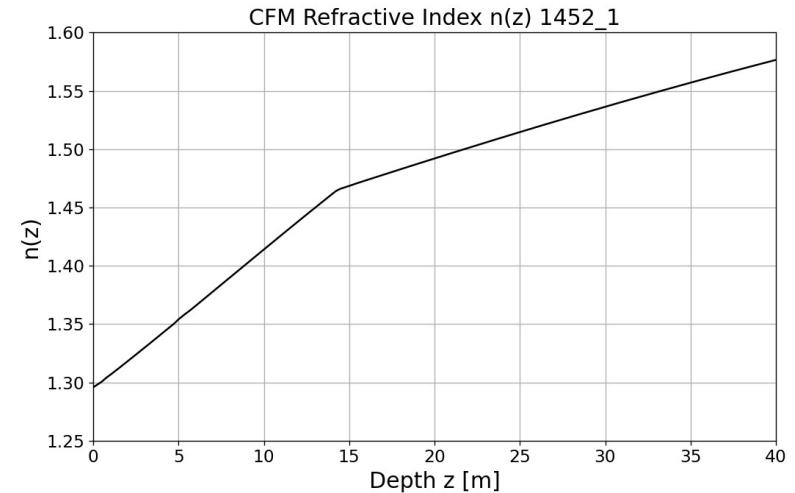
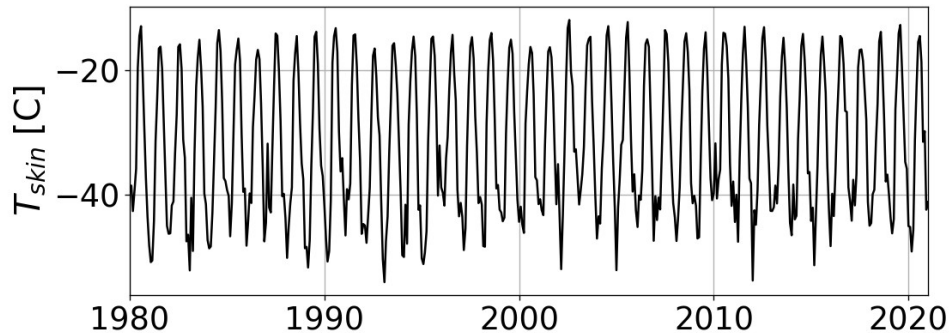
- Model time-evolving firn using climate data & glaciological simulations
- Simulation RF propagation from an in-ice source to RX array:
 - Measure changes in the RF observables
 - Run reconstruction – find systematics in energy and arrival direction



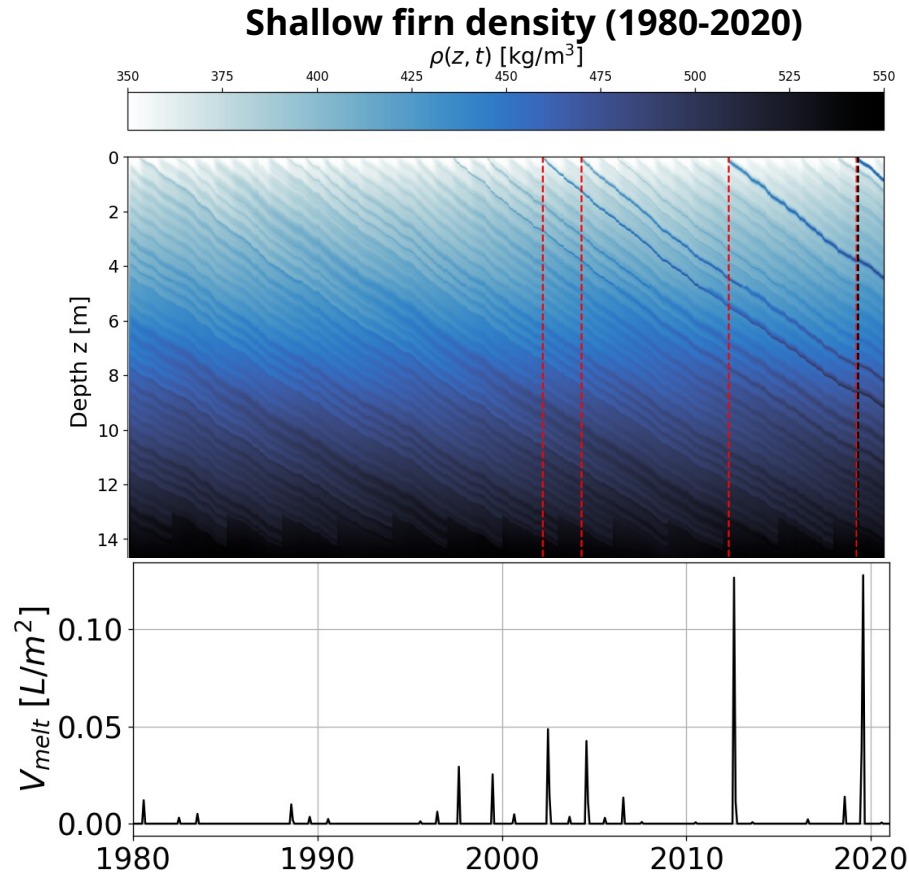
Firn Modeling – CFM inputs

Community Firn Model – glaciological simulation software

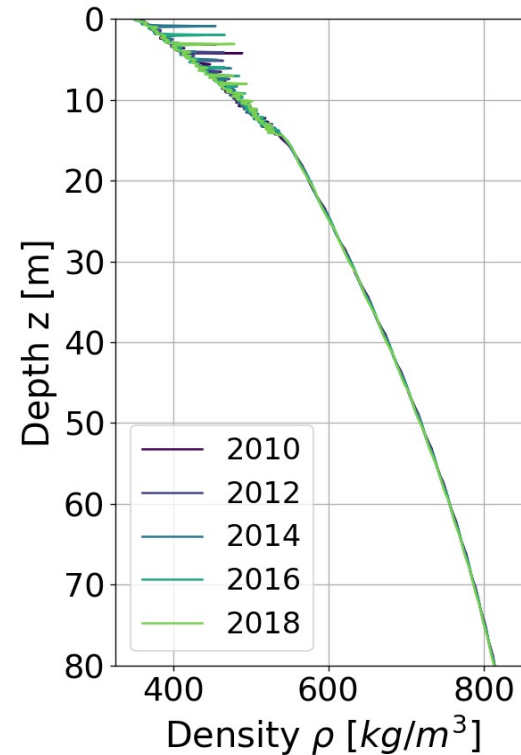
- Inputs:
 - Initial firn model
 - Monthly averaged climate data at Summit (1980 – 2020): temperature, accumulation
 - Melt events
 - Assume constant surface density $\rho_0 = 350 \text{ kg/m}^3$



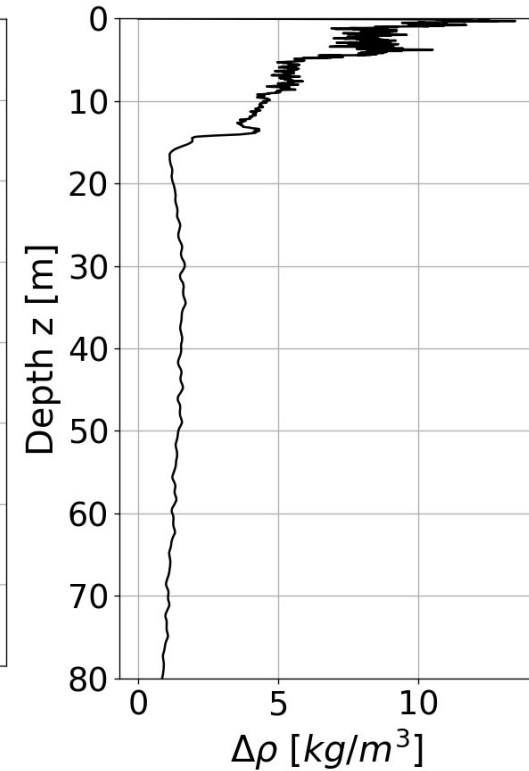
Firn Modelling – CFM results



Density profiles from CFM



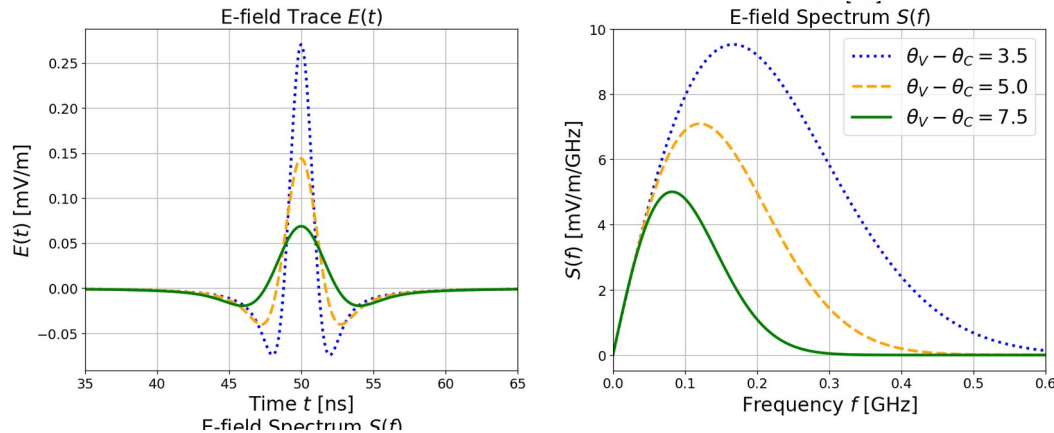
Average Variation of Density [2010-2019]



RF Simulation chain

RF Simulation

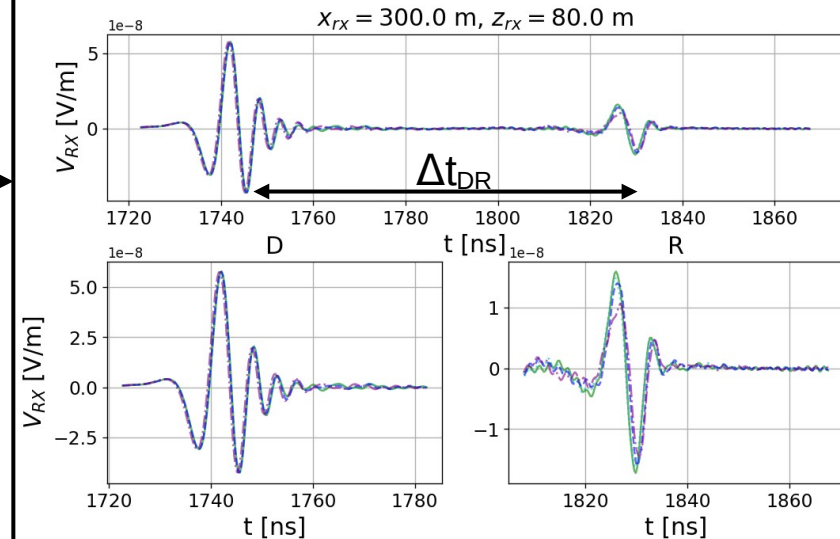
- CFM ice models → define $n(z)$ for simulation
- Test pulse: $\Delta\theta_{VC} = 7.5$ deg - ARZ parameterization
 - Band limited: 0.032 - 0.288 GHz
- Simulation methods: MEEP & paraProp



RX Observables

Defined for: primary (D) and secondary (R)

- Fluence: Φ_D, Φ_R
- Propagation times: $t_D, t_R, \Delta t_{DR}$



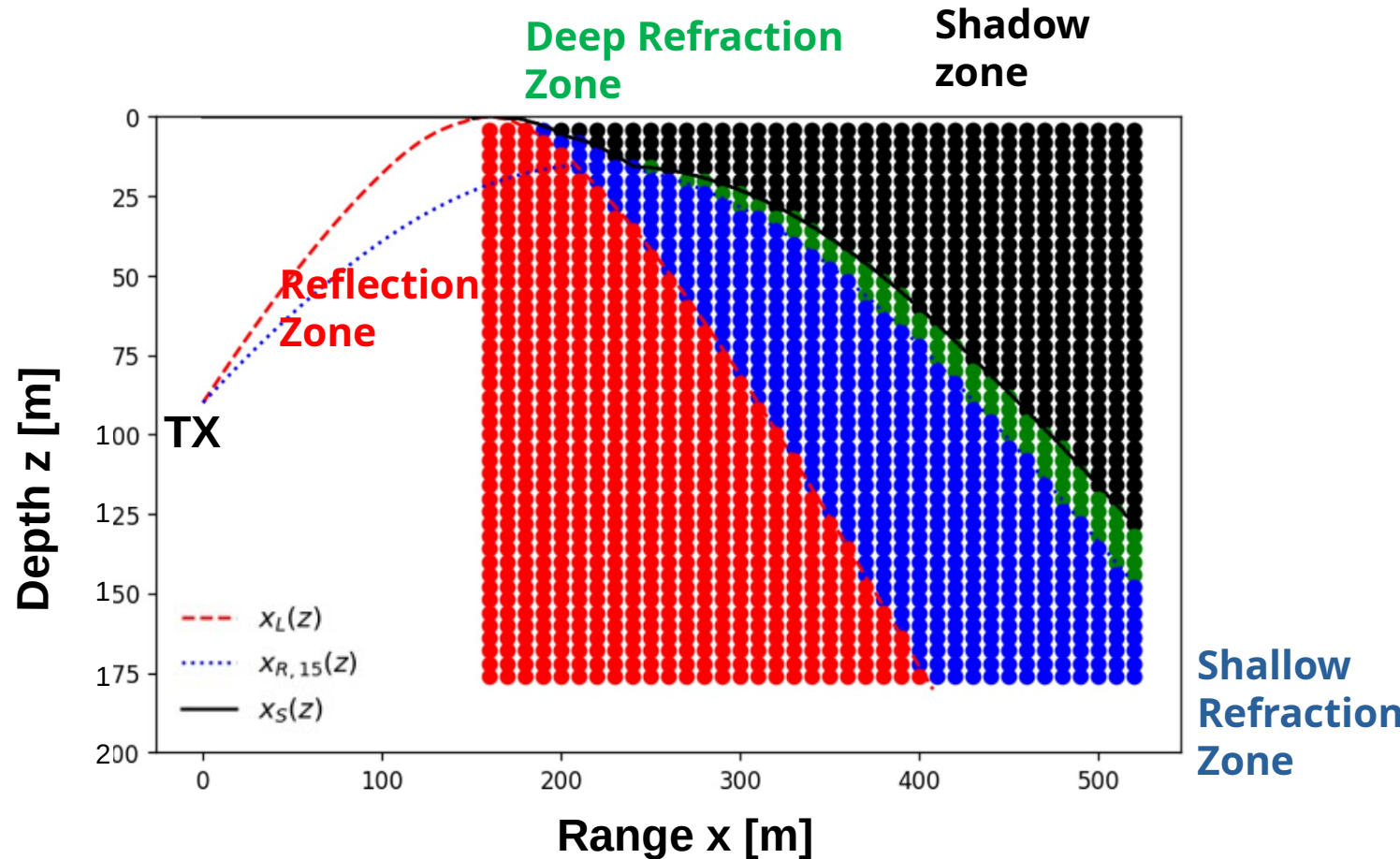
Propagation Domains – RX Array

TX at $z = 90$ m

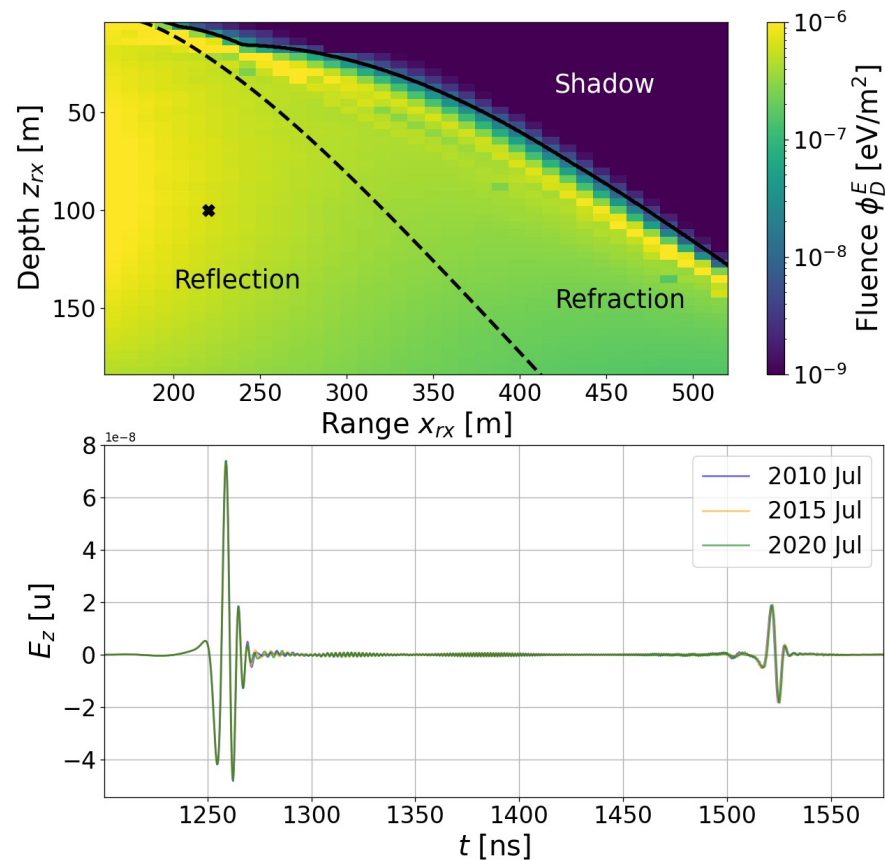
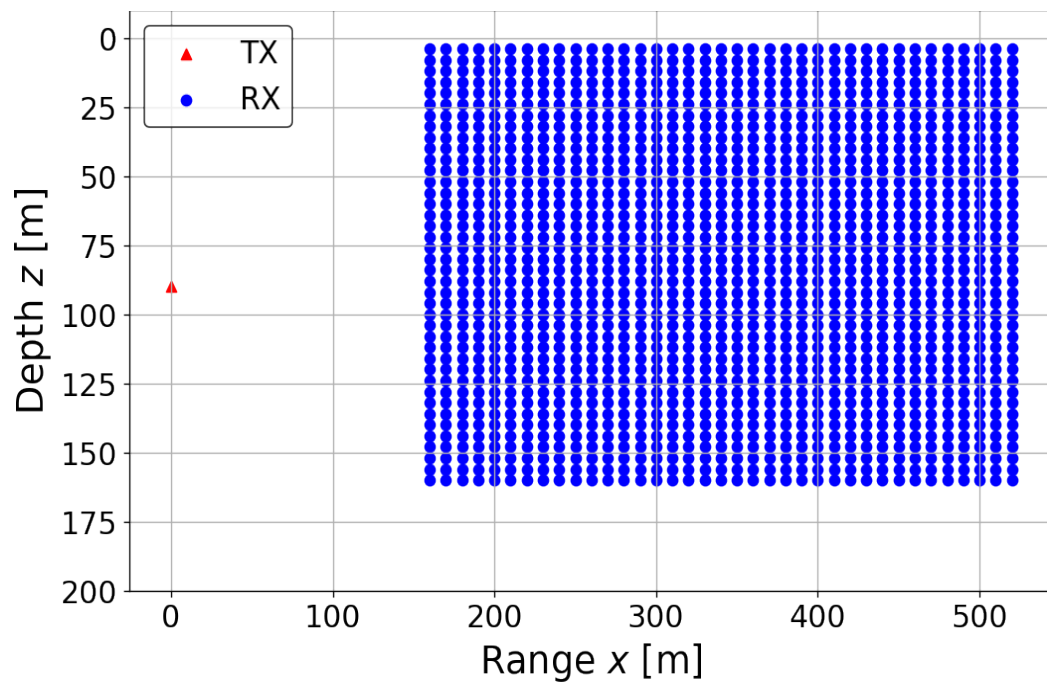
RX array

- Ranges x : 160 m – 520 m (10 m spacing)
- Depths z : 4 m – 180 m (4 m spacing)

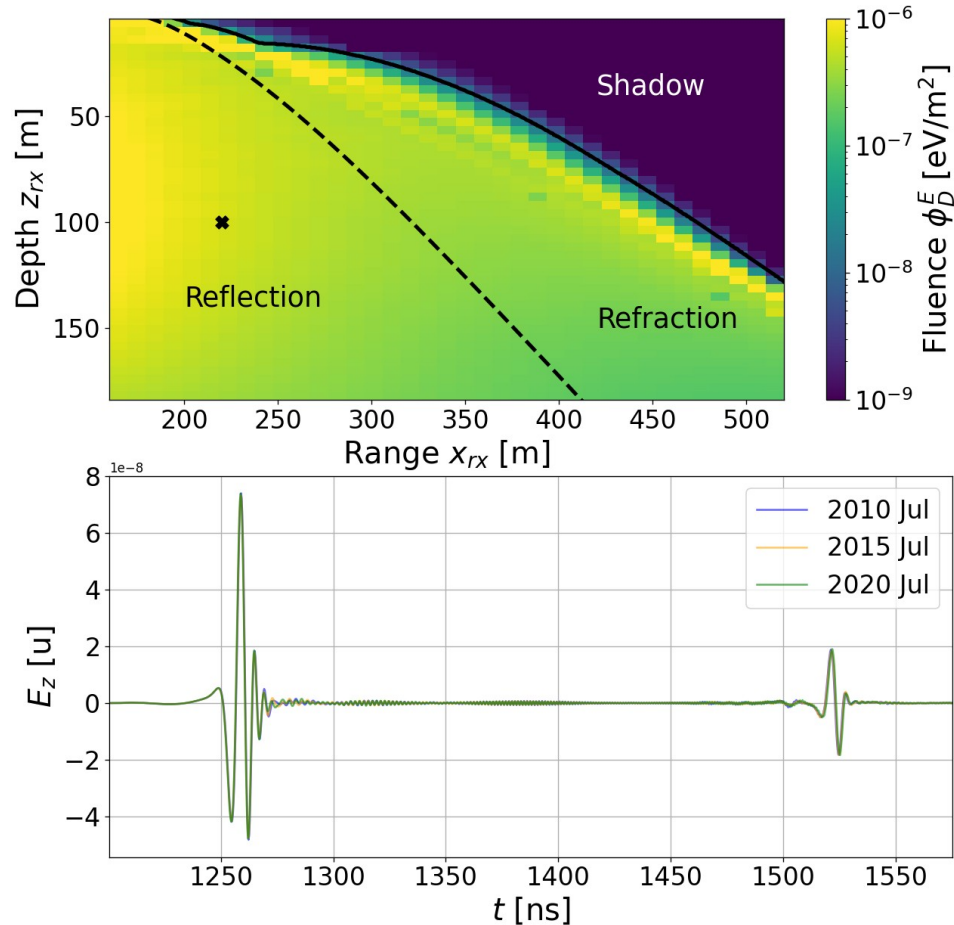
Propagation domain defined by secondary pulse



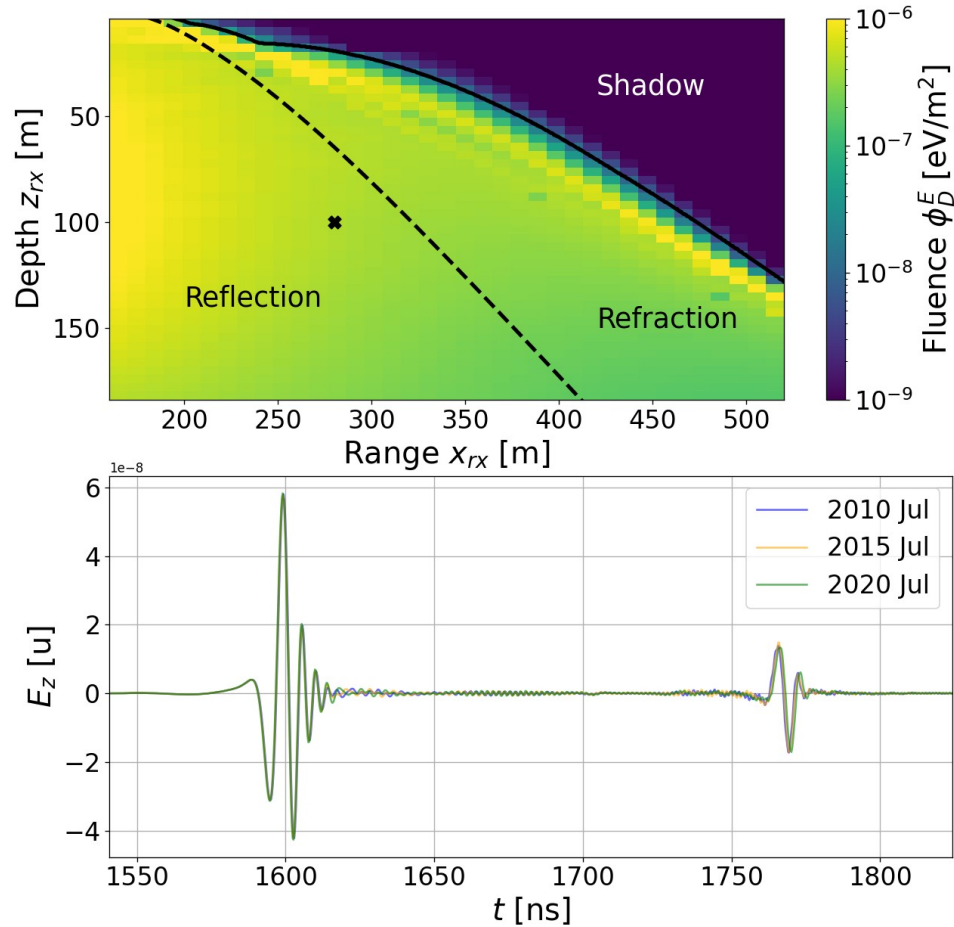
Propagation Zones



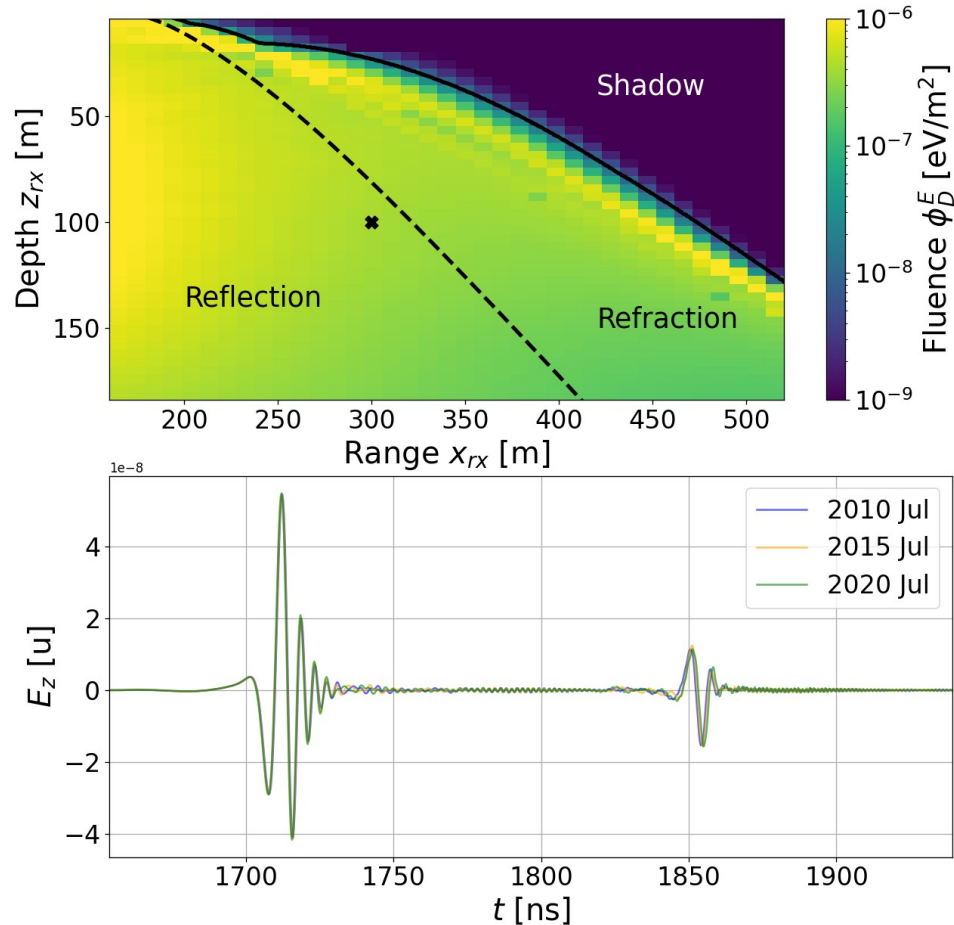
Pulse at RX($x = 220$ m, $z = 100$ m)



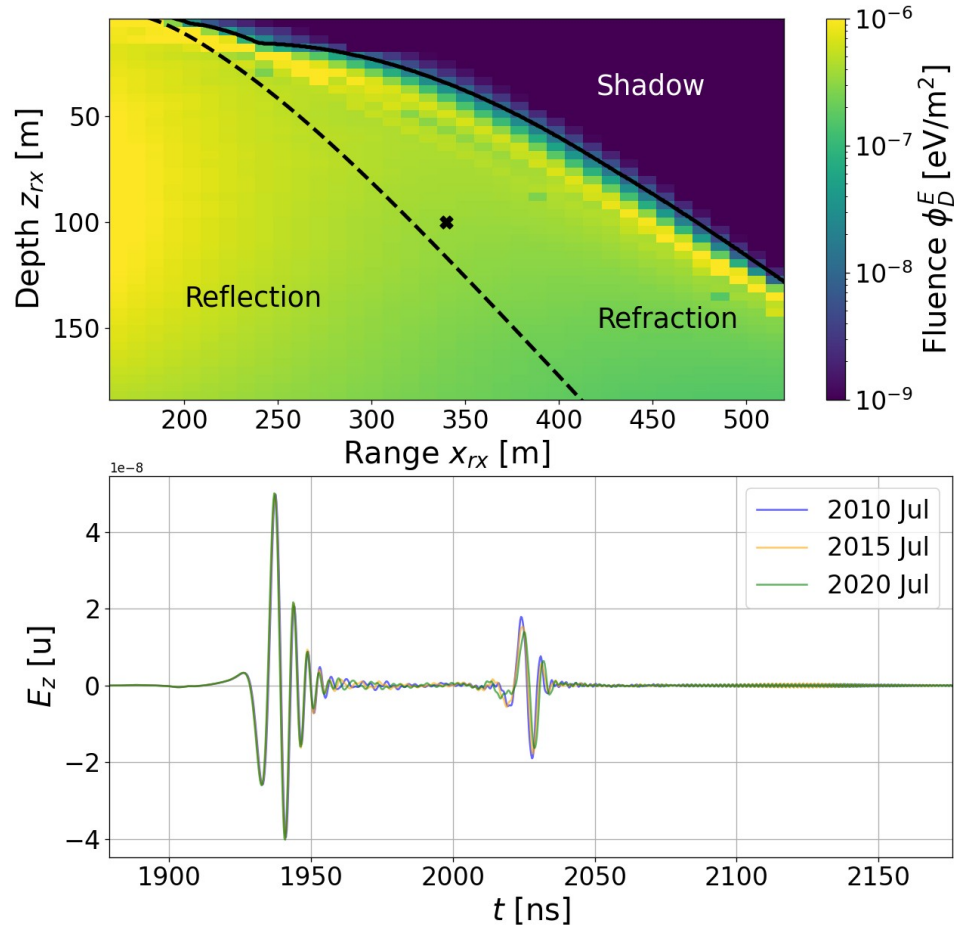
Pulse at RX($x = 280$ m, $z = 100$ m)



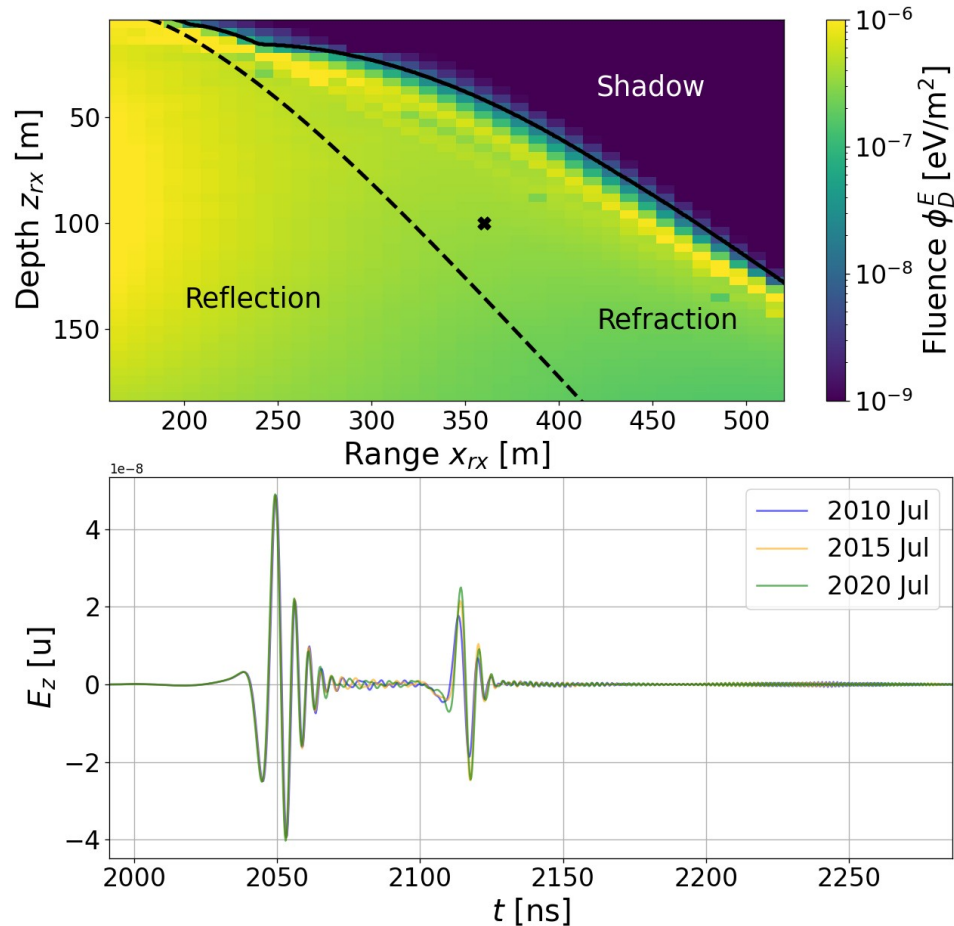
Pulse at RX($x = 300$ m, $z = 100$ m)



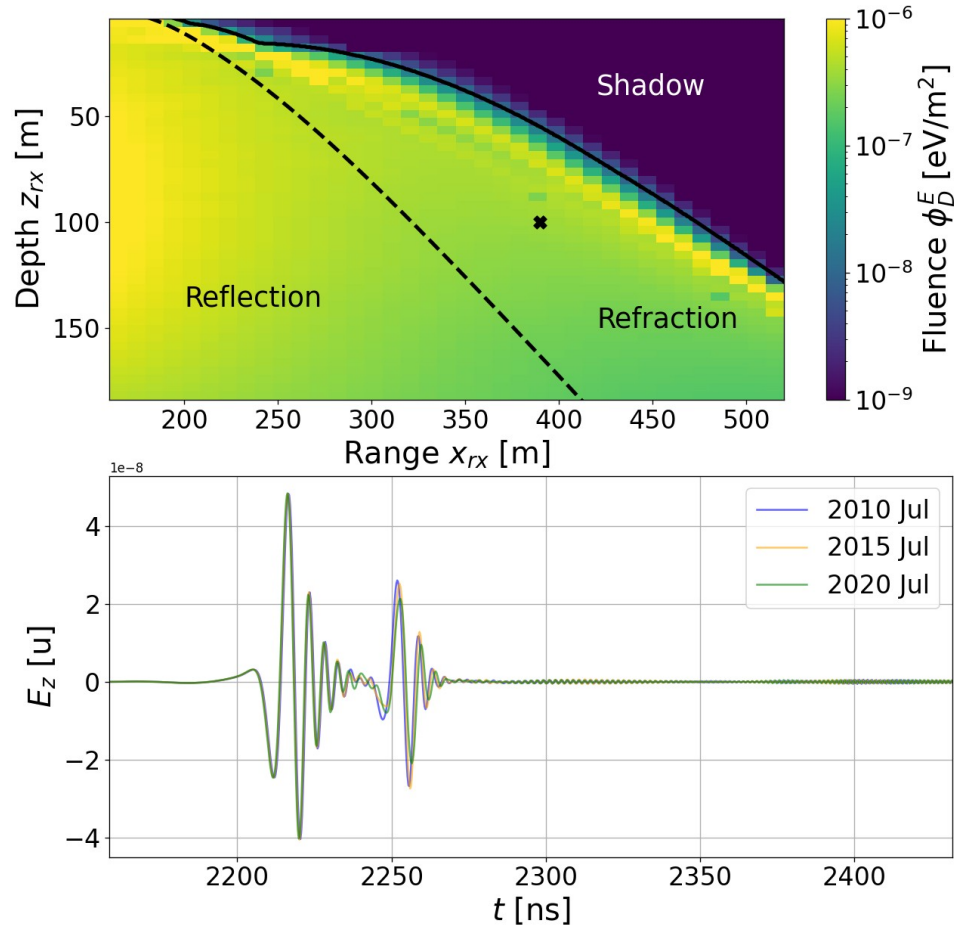
Pulse at RX($x = 340$ m, $z = 100$ m)



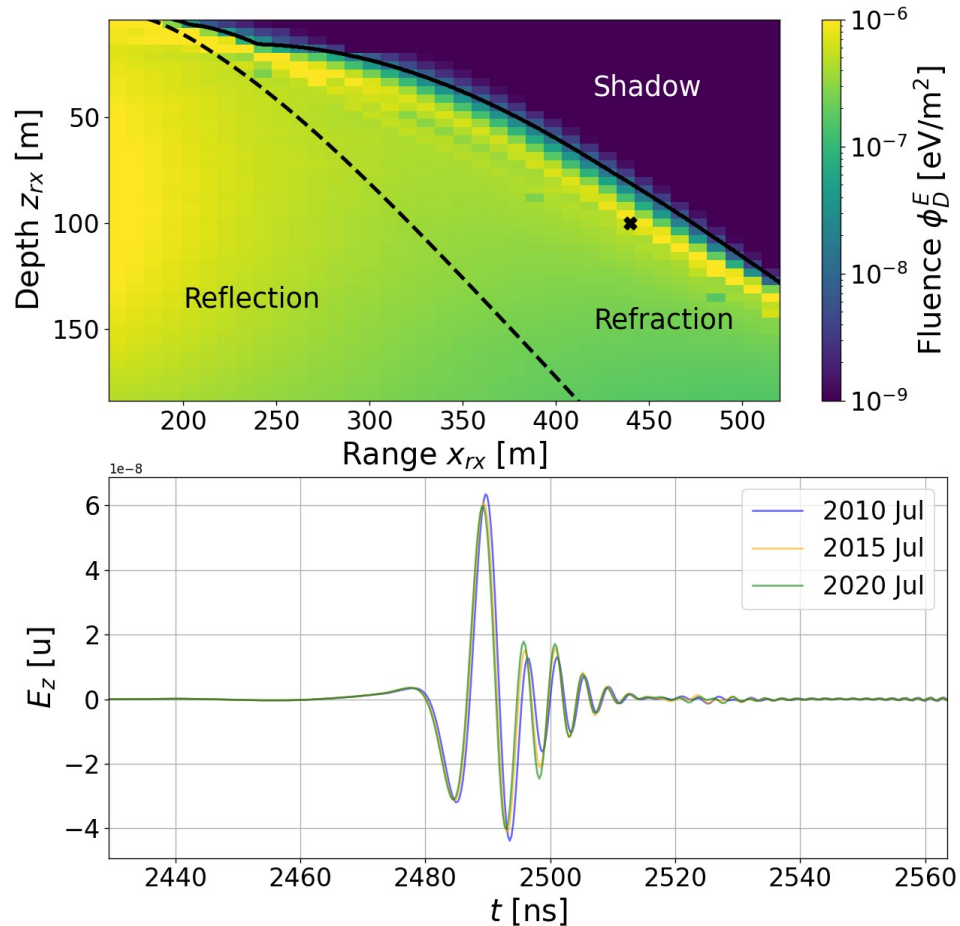
Pulse at RX($x = 360$ m, $z = 100$ m)



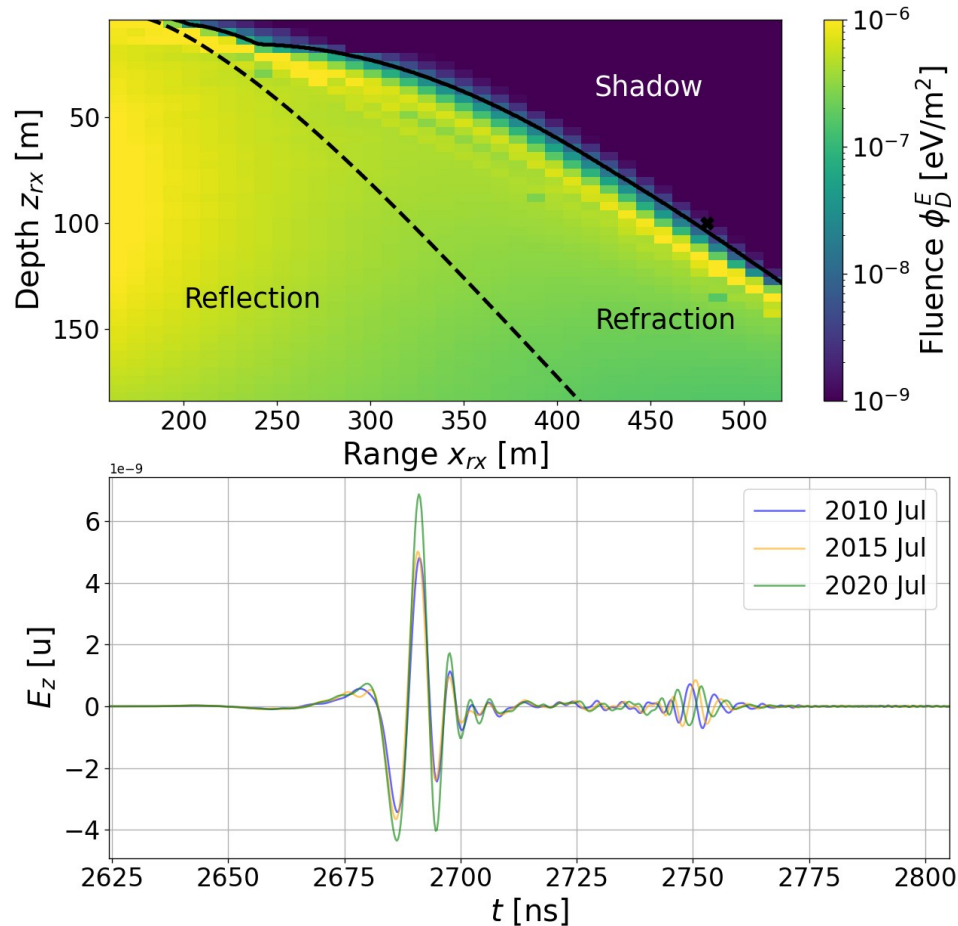
Pulse at RX($x = 400$ m, $z = 100$ m)



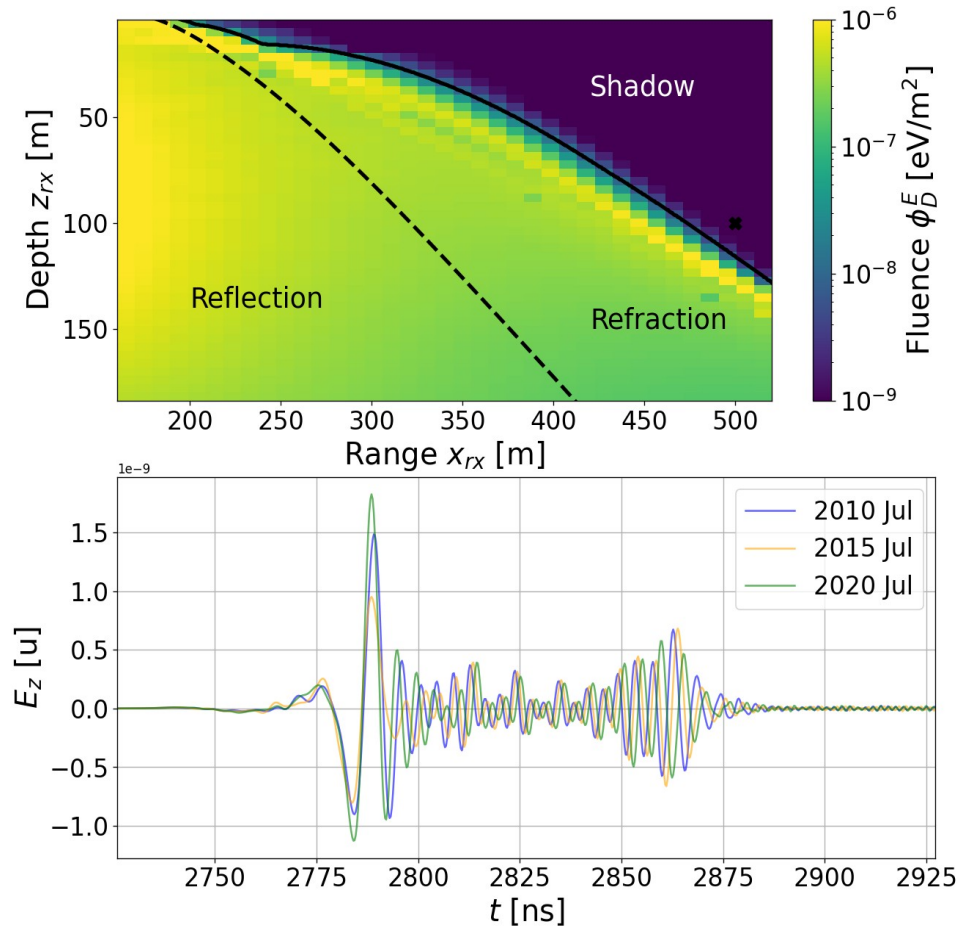
Pulse at RX($x = 440$ m, $z = 100$ m)



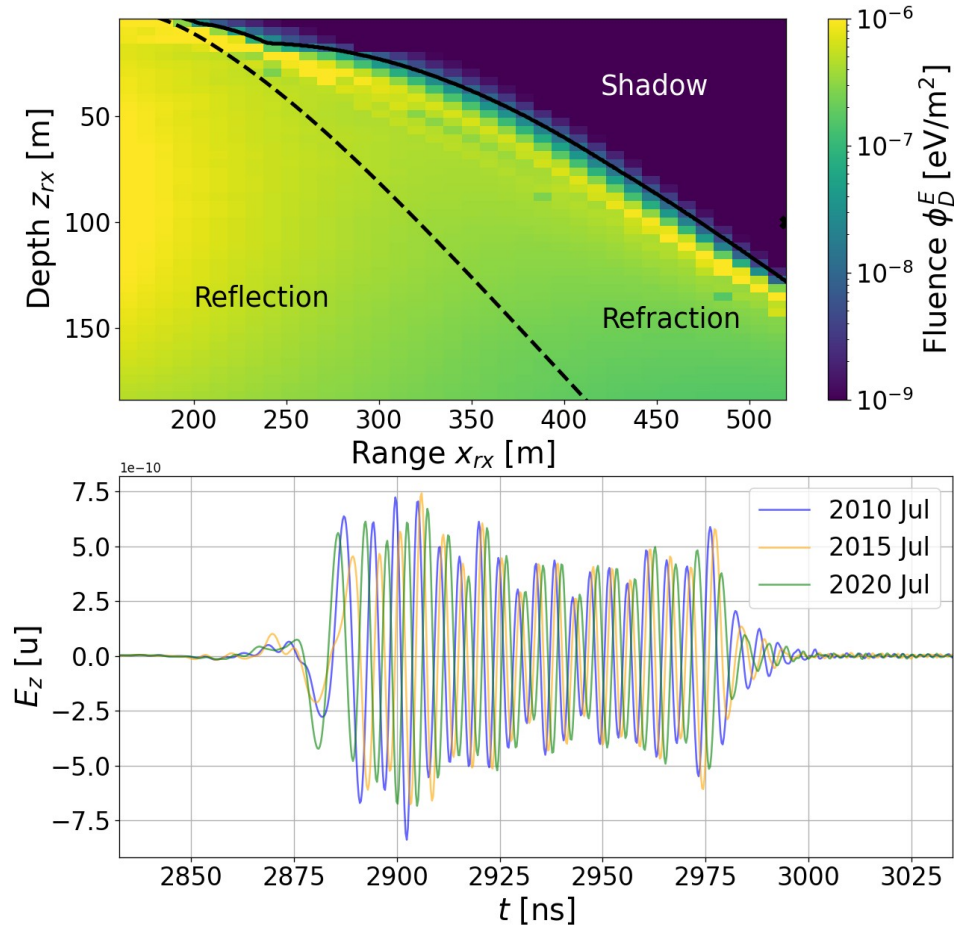
Pulse at RX($x = 480$ m, $z = 100$ m)



Pulse at RX($x = 500$ m, $z = 100$ m)

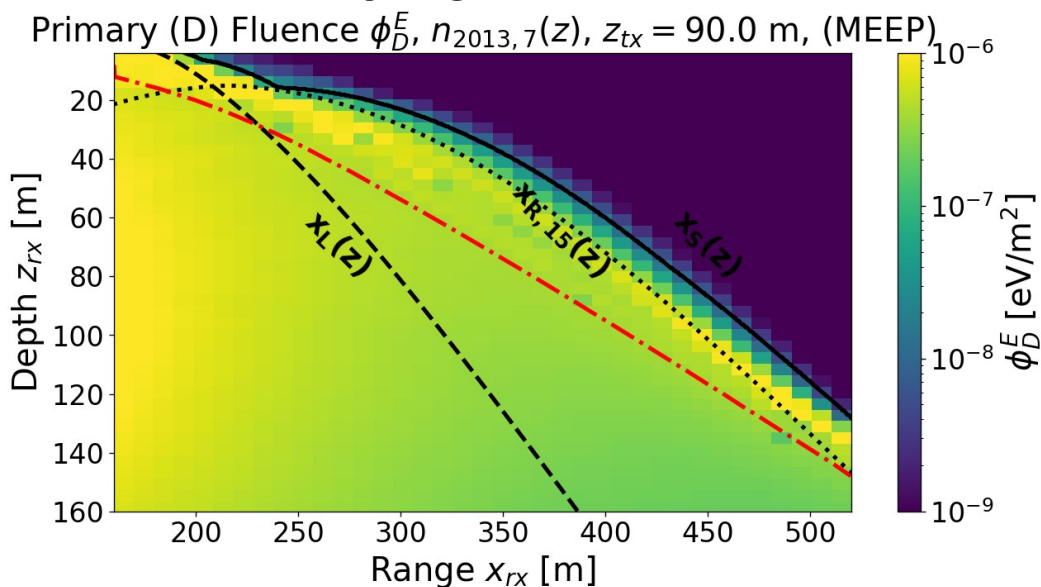


Pulse at RX($x = 520$ m, $z = 100$ m)

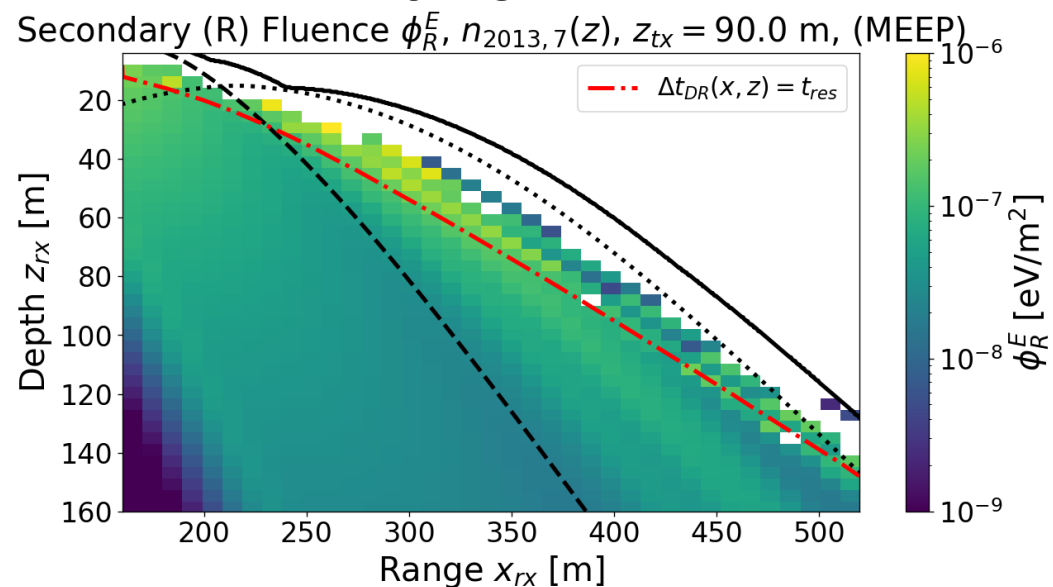


Fluence – 2013, 7

Primary signal fluence Φ_D

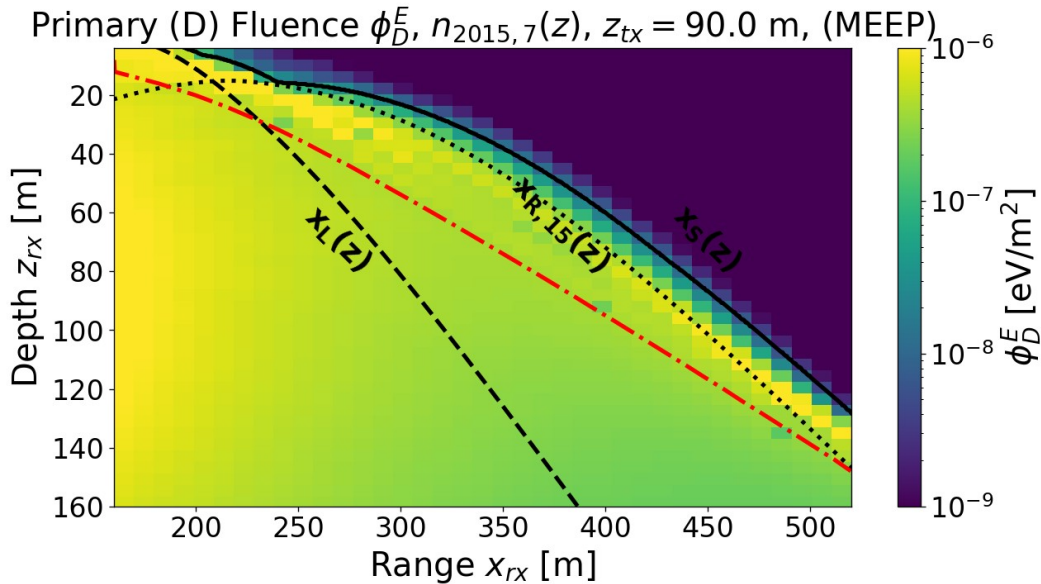


Secondary signal fluence Φ_R

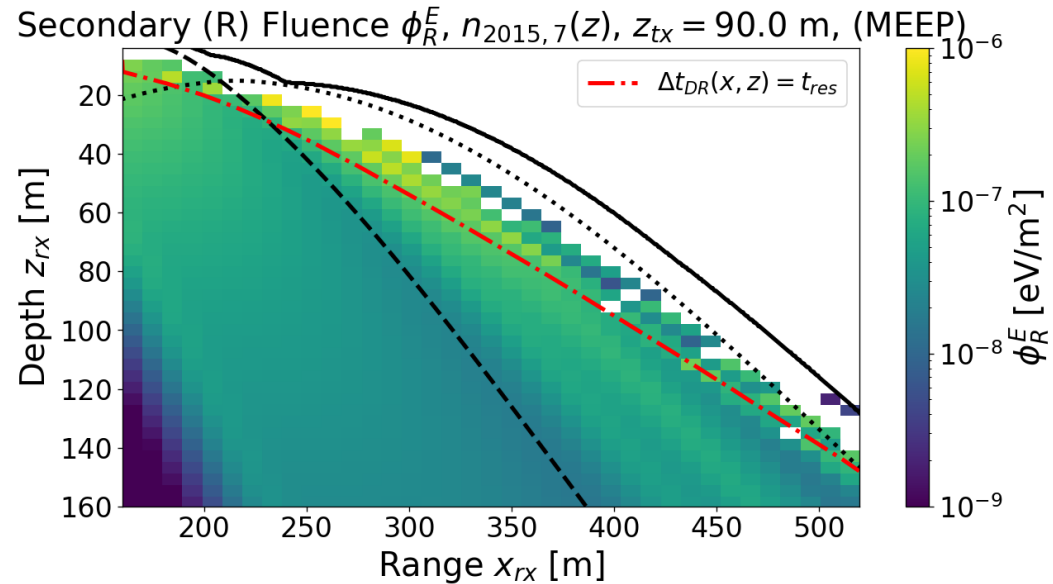


Fluence – 2015, 7

Primary signal fluence Φ_D

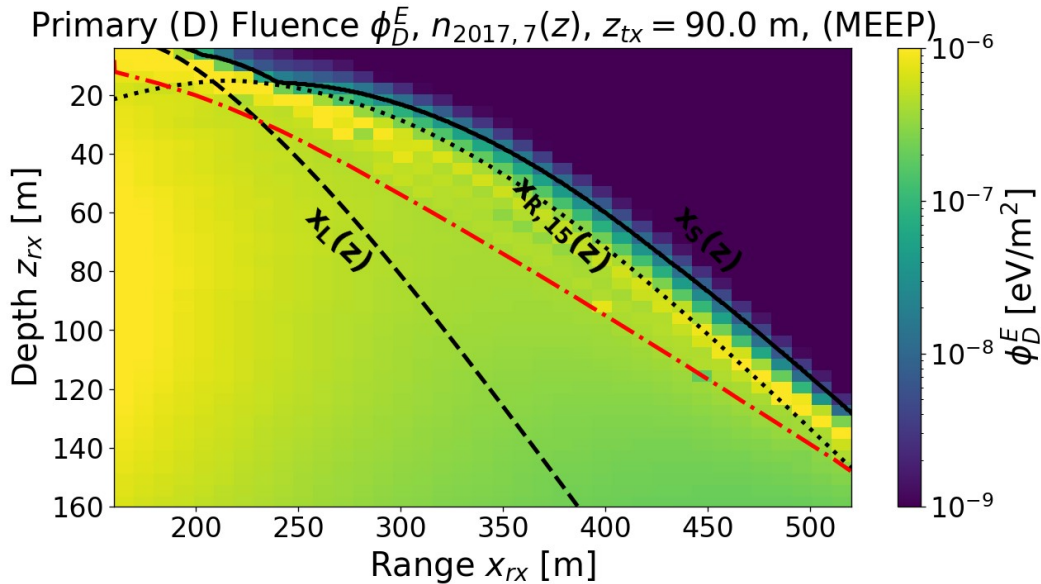


Secondary signal fluence Φ_R

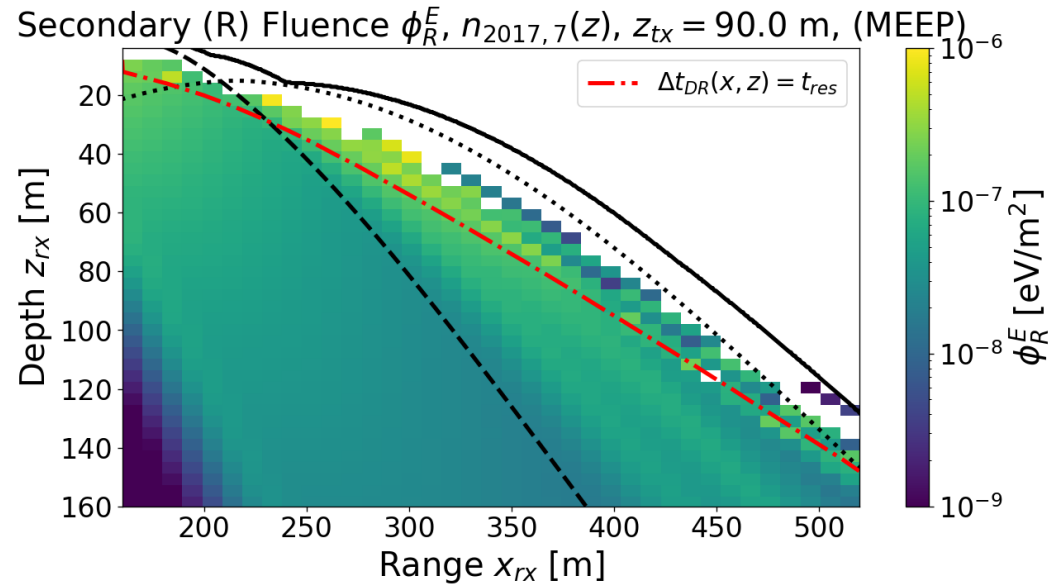


Fluence – 2017, 7

Primary signal fluence Φ_D

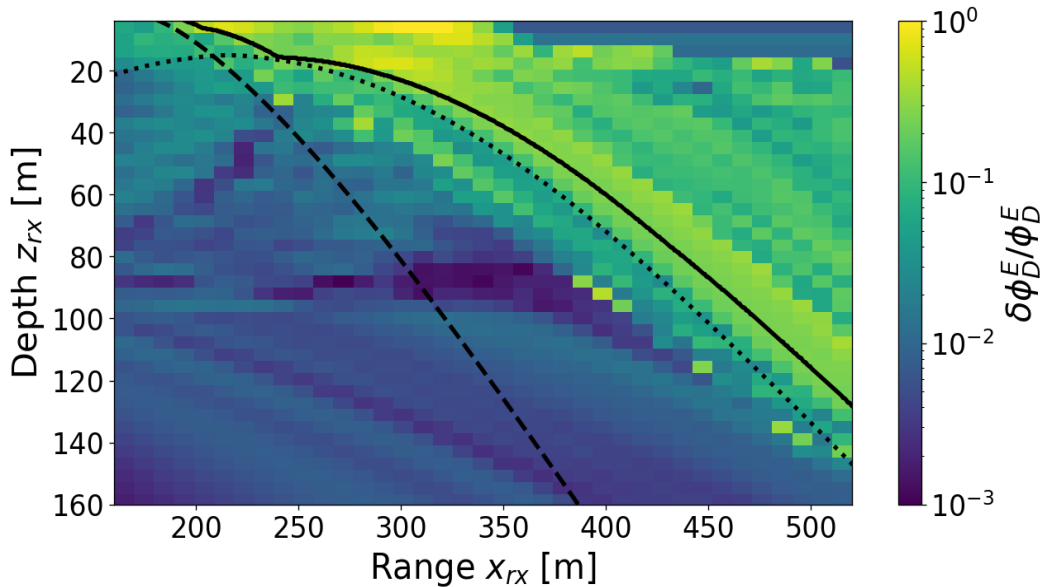


Secondary signal fluence Φ_R

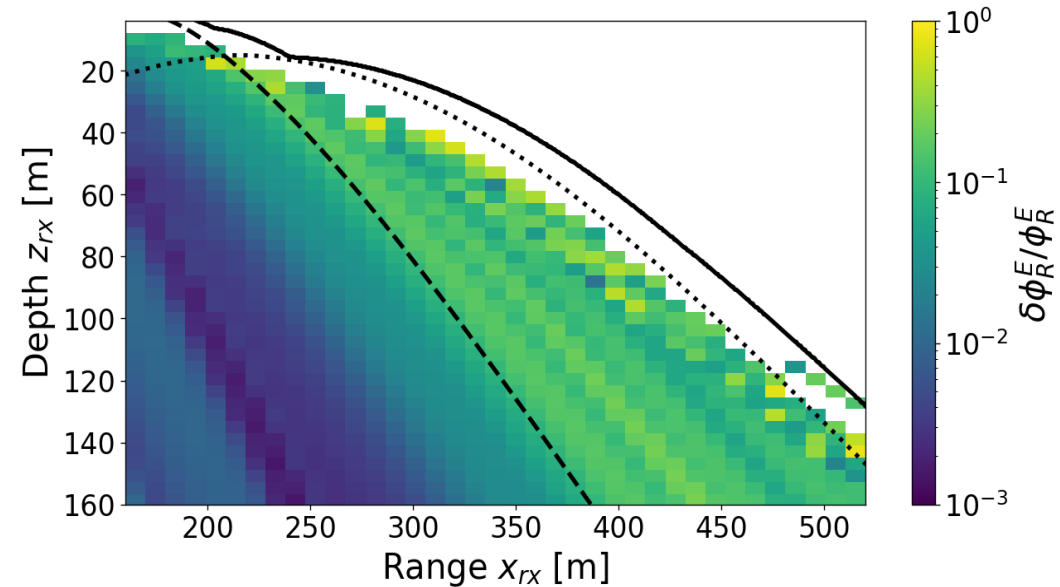


Fluence Variation

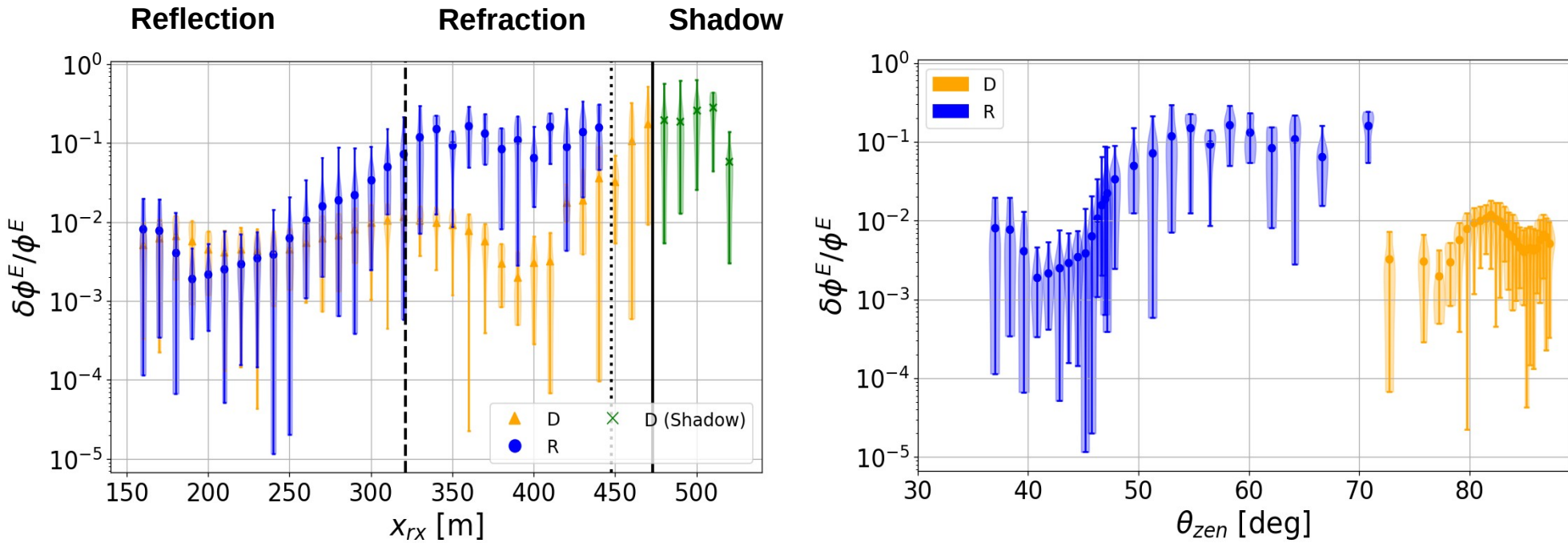
Primary signal (D) variation
 $\delta\Phi_D/\Phi_D$



Secondary signal (R) variation
 $\delta\Phi_R/\Phi_R$

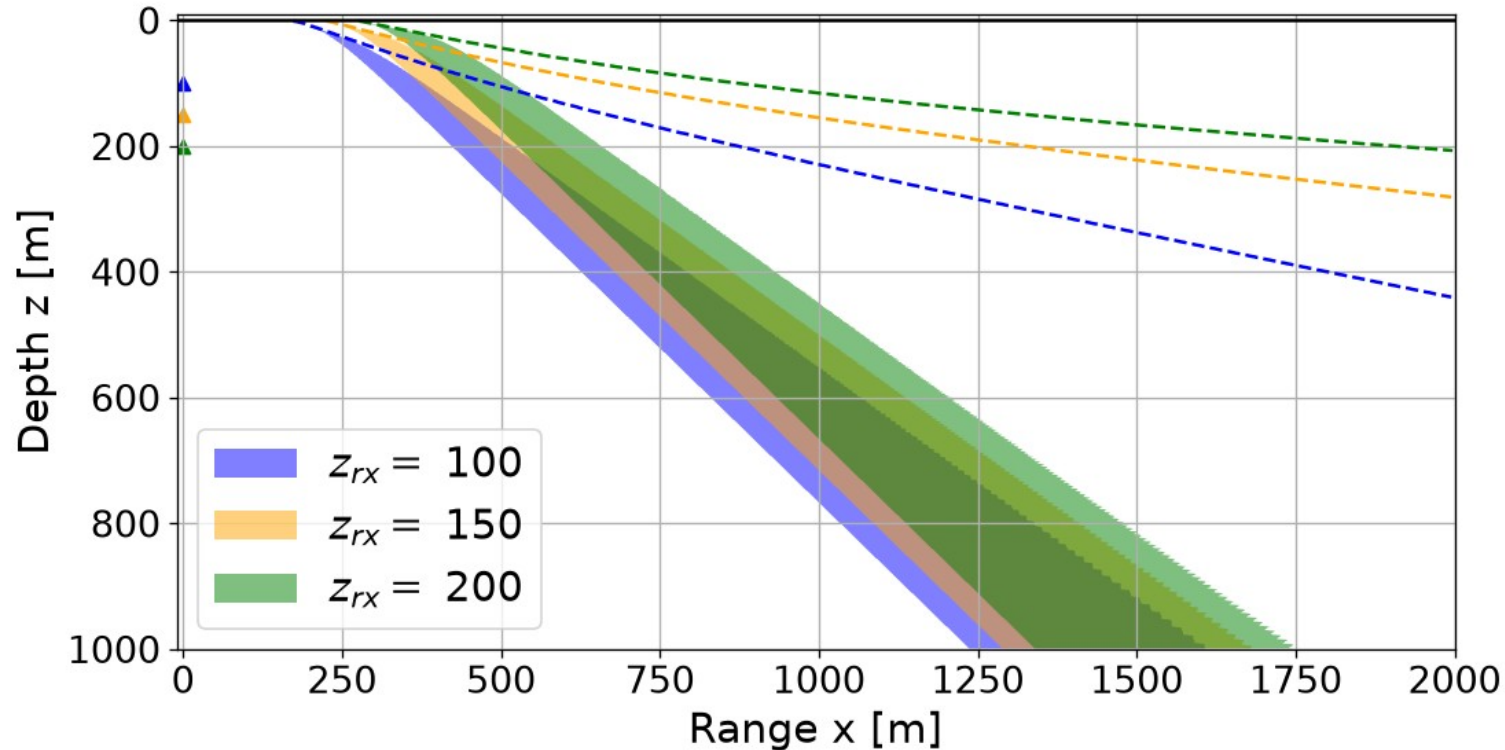


Fluence variation at $z_{rx} = 100$ m



Implications Neutrino Detectors

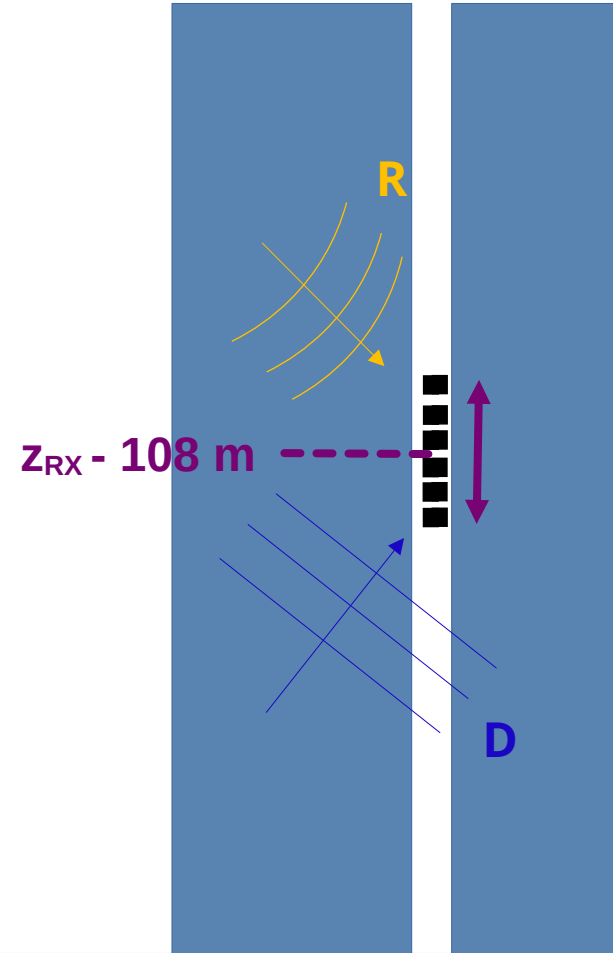
18% of neutrinos in a cylinder of $r = 3$ km, $z = 2.7$ km result in such signal paths



Neutrino Reconstruction

Reconstruction method:

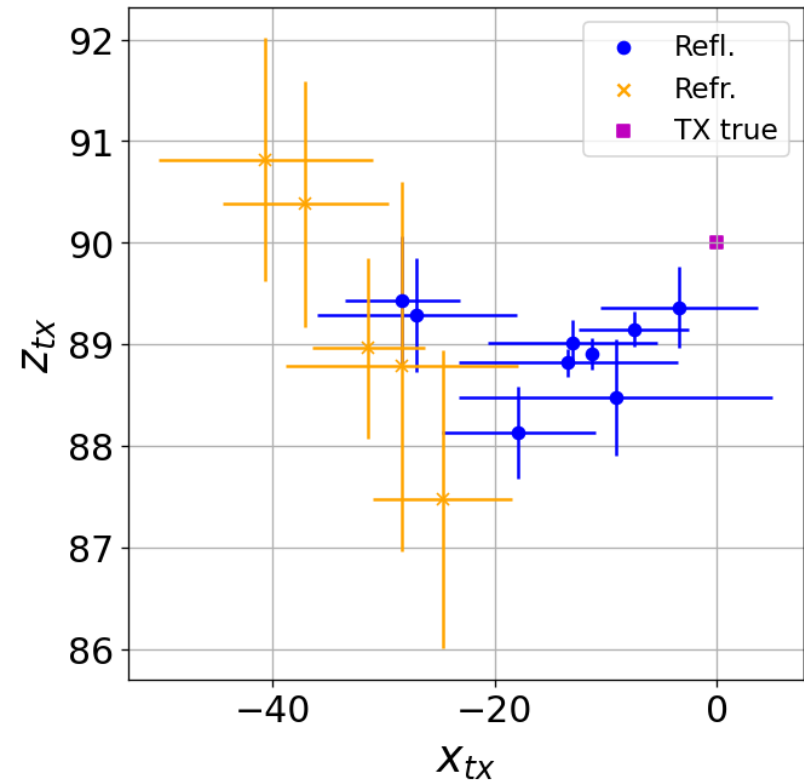
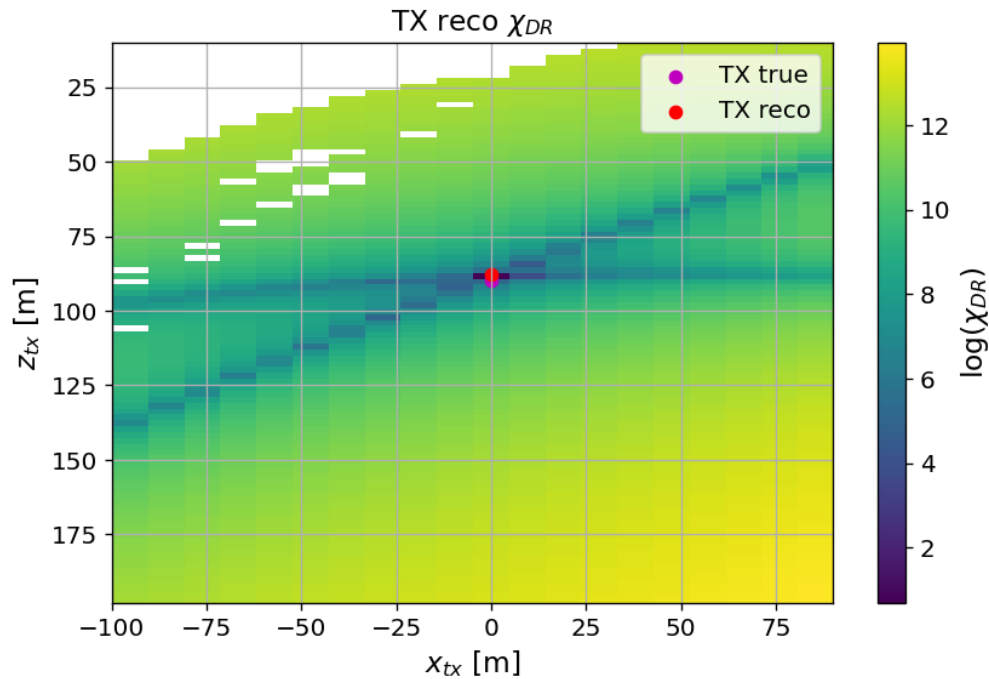
1. Take 6 Vpol antennas as a phased array
2. Vertex reconstruction:
 1. Find a best fit TX through RT
 2. Variation in L & θ_{RX}
3. Coherent sum across the waveforms (D & R)
4. $\Delta\theta_{VC}$ from slope parameter method (C. Welling et al JCAP10(2019)075)
5. Find variation in spectral parameters from coherently summed waveforms



Vertex Reconstruction

Ray-tracing (RadioPropa) → relative propagation times ($t_D - t_{D0}$ & $t_R - t_{R0}$)

Find TX with chi-squared fit

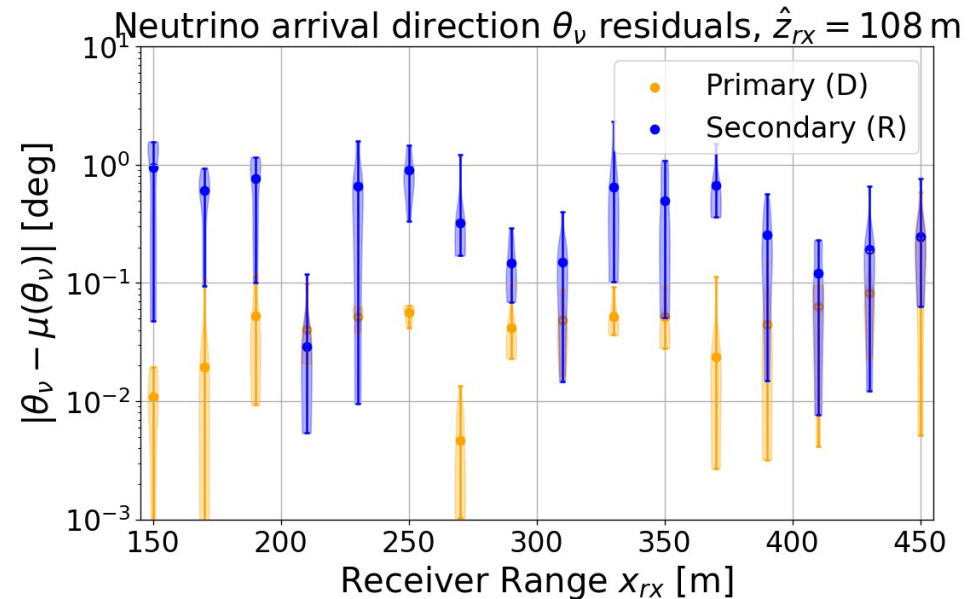
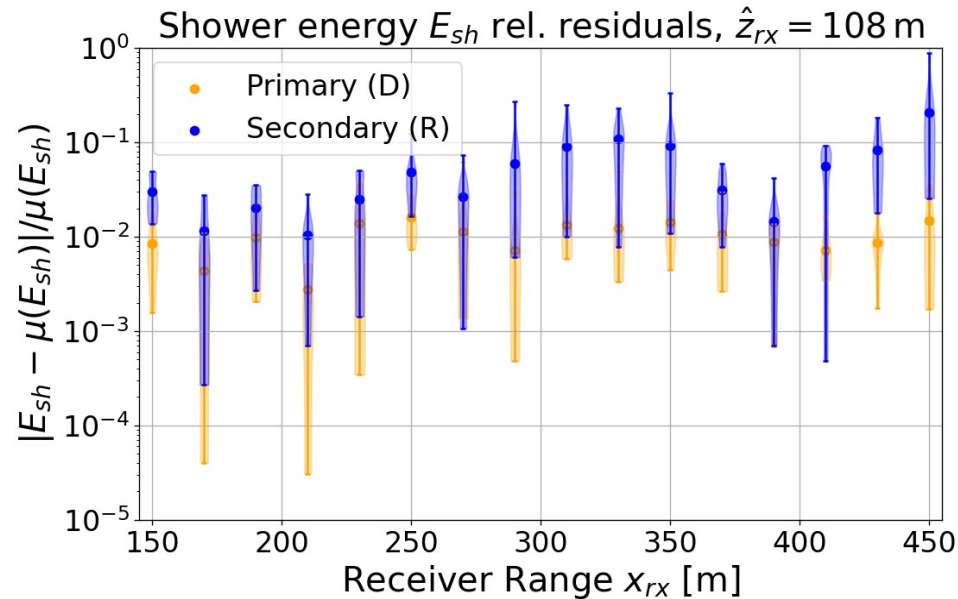


Energy and Arrival Direction

$\delta E_{sh}/E_{sh} \sim 0.01$ (D-only), $\delta E_{sh}/E_{sh} \sim 0.1$ (R-only)

$\delta \theta_v < 0.1^\circ$ (D-only), $0.1^\circ < \delta \theta_v < 1^\circ$ (R-only)

- similar to previous studies on ice property systematics: Aguilar et al. Eur. Phys. J. C (2022) 82: 147



Outlook

Detector specific analysis is required to properly derive the systematic uncertainties from ice variation, accounting for

- Noise
- Antenna effects & signal chain
- Specific detector geometry

Polarization was neglected in this analysis:

- Proper treatment requires simulation of $\mathbf{E}_\phi$
- MEEP and paraProp relied upon cylindrical symmetry – only simulate $\mathbf{E}_\theta$

Shadow zone reconstruction is exceedingly difficult – requires a TX reconstruction method independent of ray-tracing

Summary

Take away message:

In the absence of an up-to-date ice model firn evolution leads to an inherent background uncertainty in neutrino reconstruction using refracted signals

- Fluence and energy variation strongest for 'shallow refracting' signals
- For our 6 Vpol RX string & optimistic assumptions:
 - Shower energy uncertainty: $0.01 \lesssim \delta E_{\text{sh}}/E_{\text{sh}} \lesssim 0.1$
 - Arrival direction: $0.1^\circ \lesssim \delta \theta_v \lesssim 1^\circ$
- Polarization merit further investigation
- CR radio signals must pass through shallow firn

Full analysis details: Kyriacou, Prohira & Besson (2026), arXiv:2602.08921

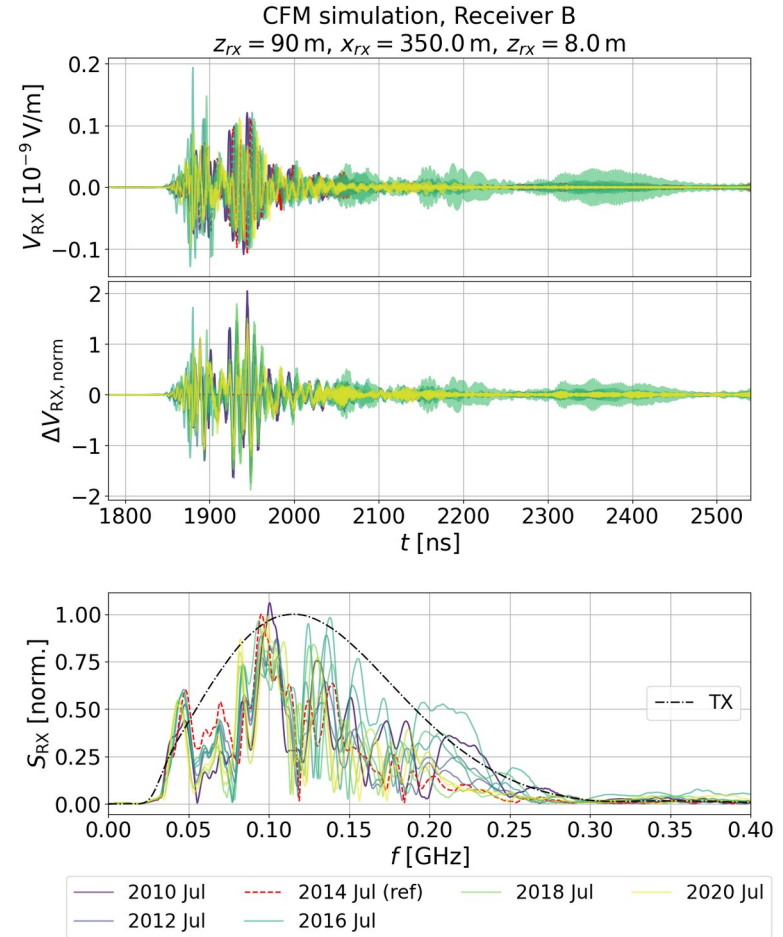
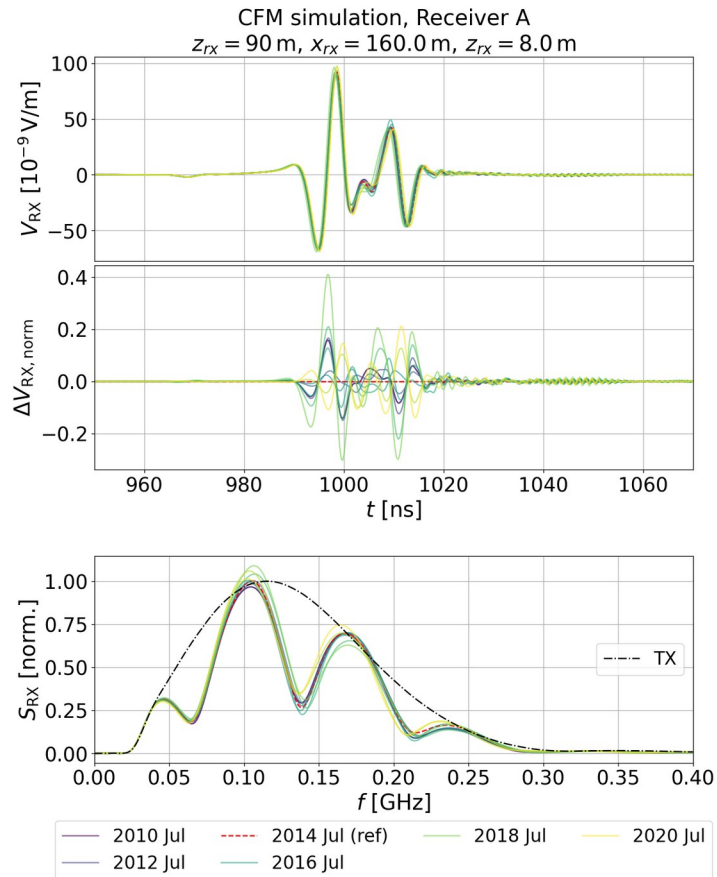
Accepted for publication in Physical Review D

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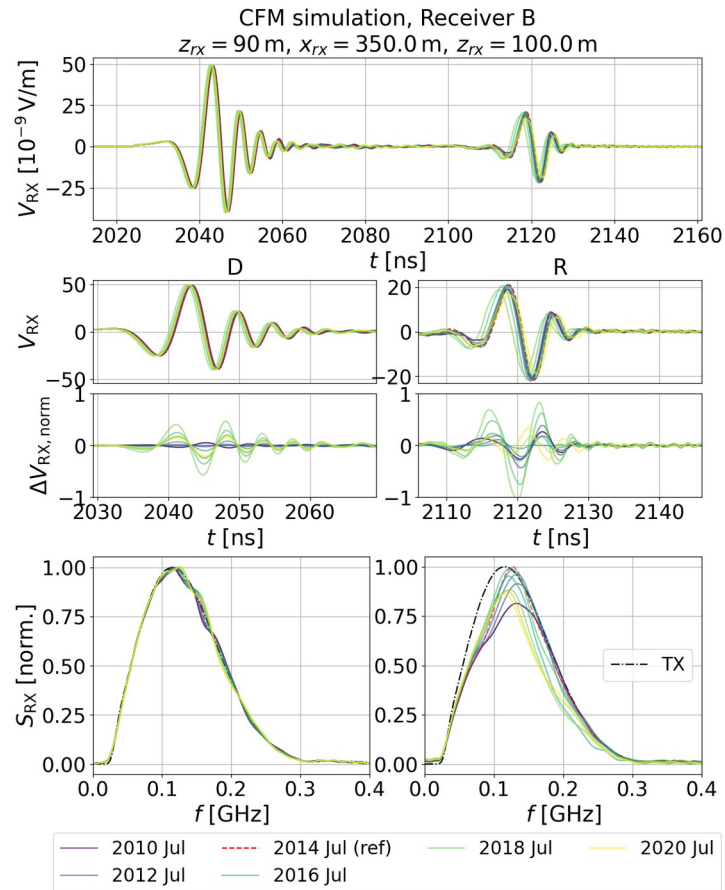
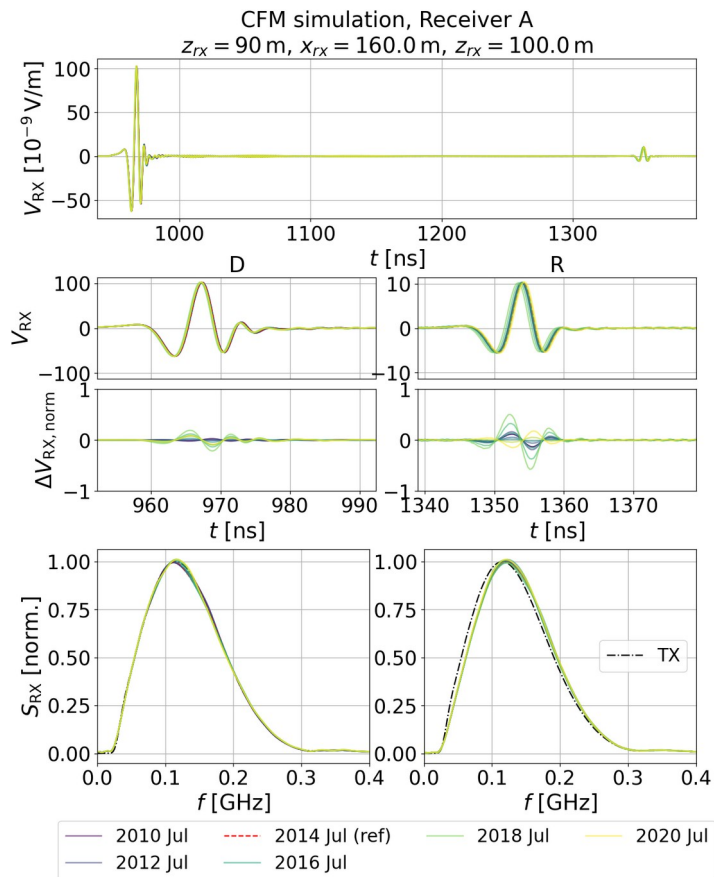
Backup Slides



Shallow Antennas ($z_{rx} = 8$ m)



Deep Antennas ($z_{rx} = 100$ m)



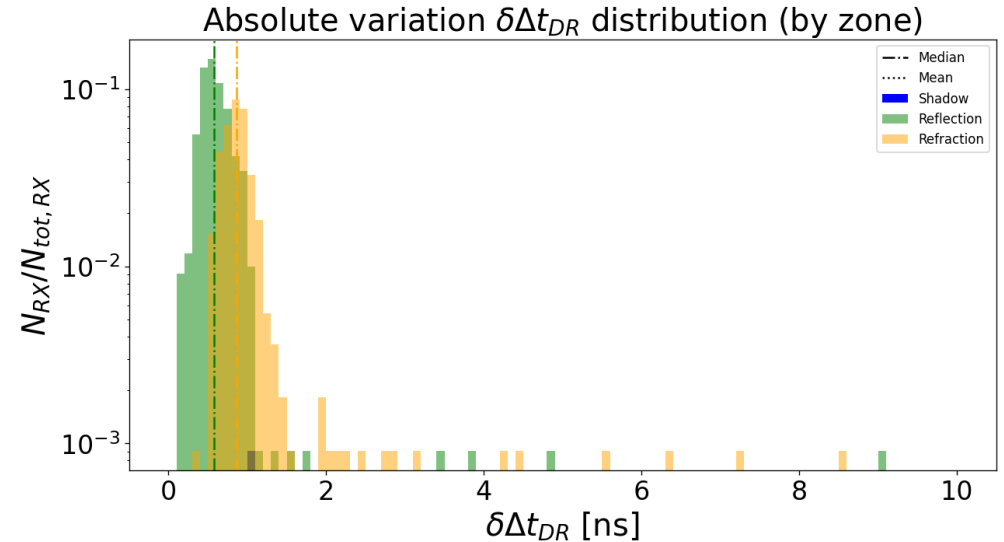
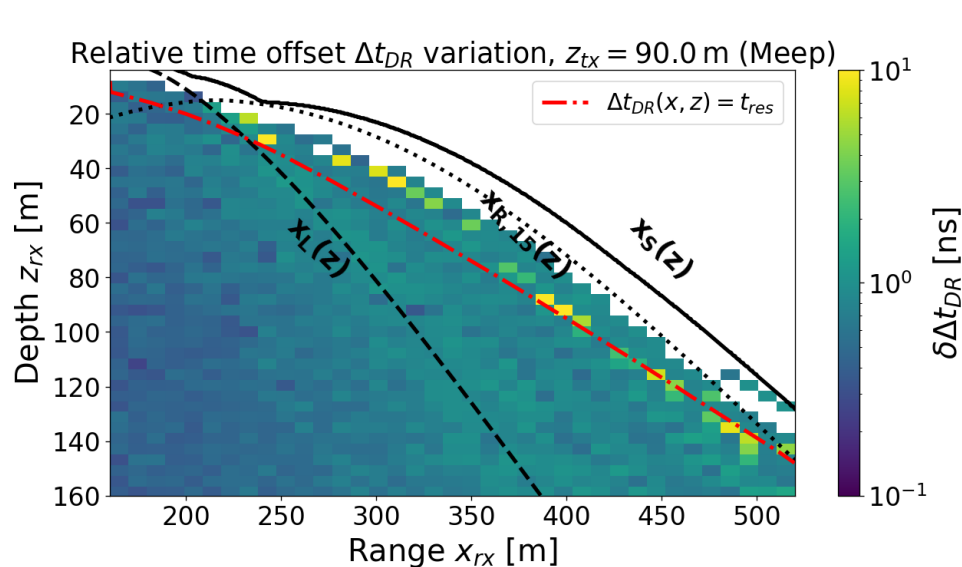
Propagation Time

Relative propagation time (from time of max amplitude for D and R):

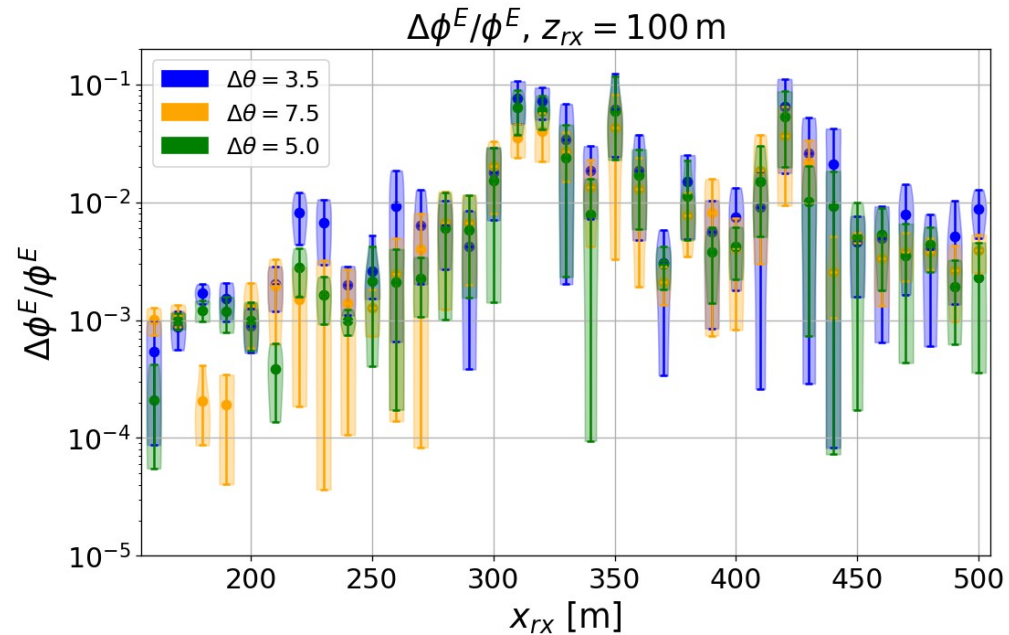
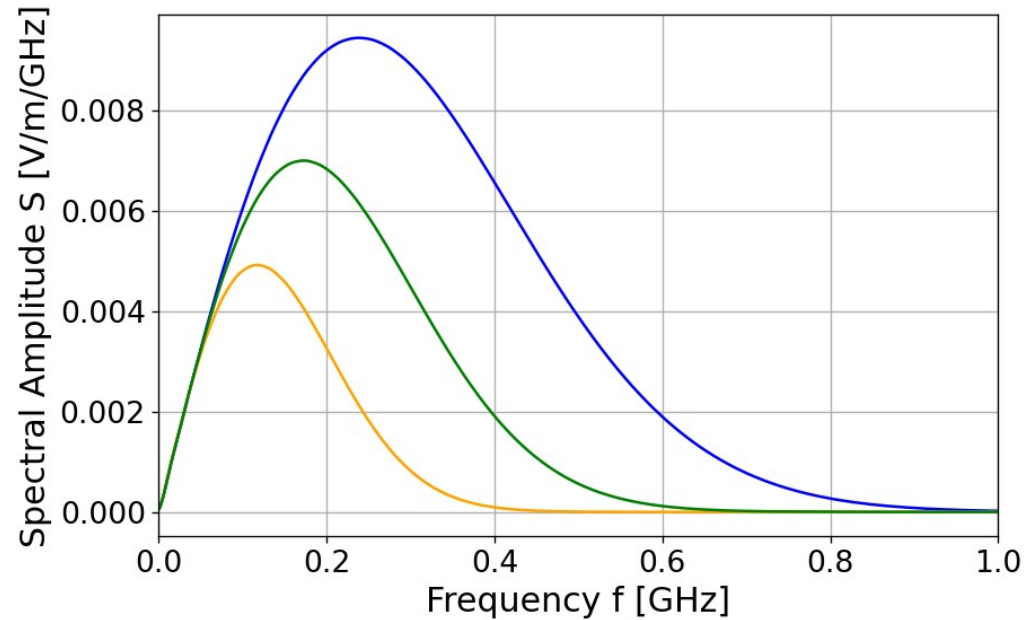
Variation across models is moderate:

-Reflection zone: $\delta\Delta t_{DR} \sim 0.6$ ns

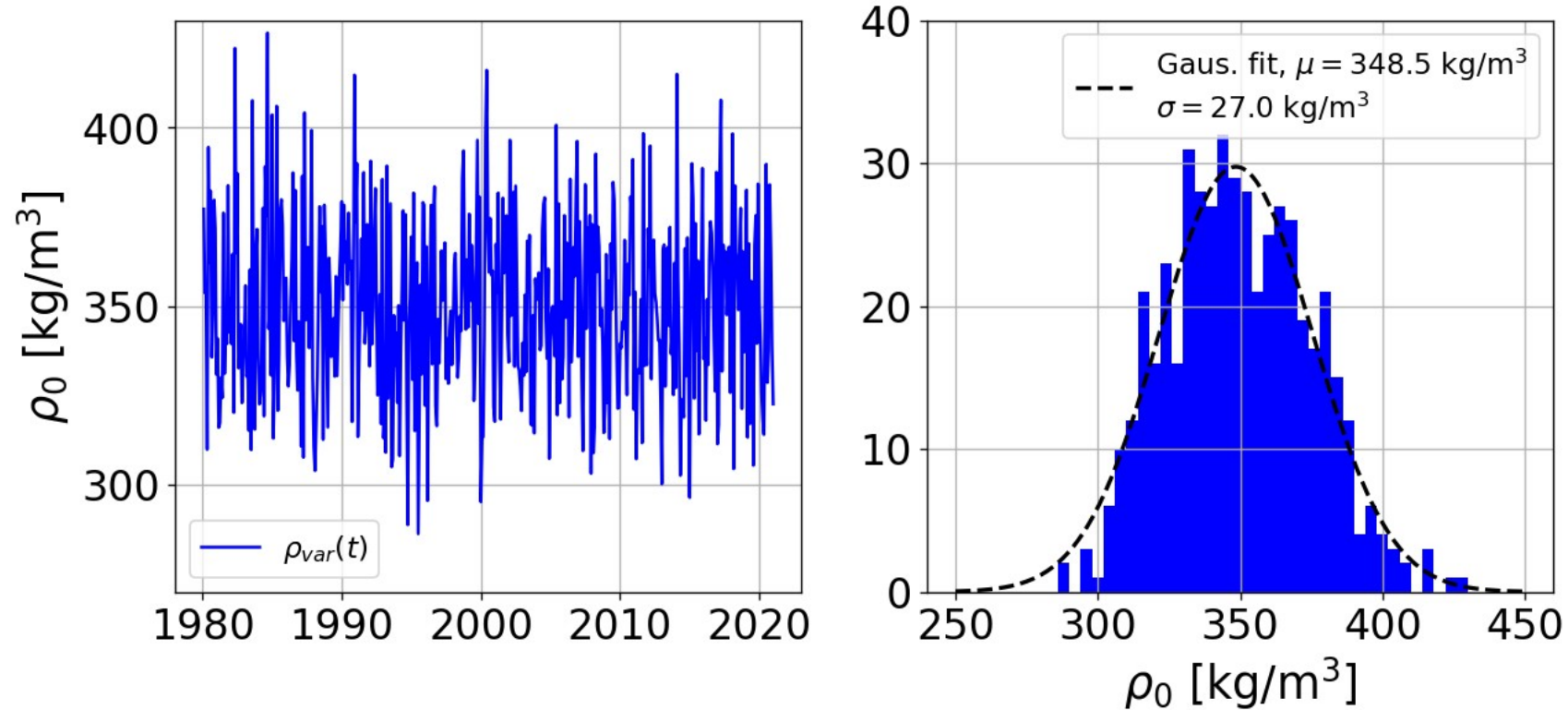
-Refraction zone: $\delta\Delta t_{DR} \sim 1.2$ ns



Bandwidth Dependence

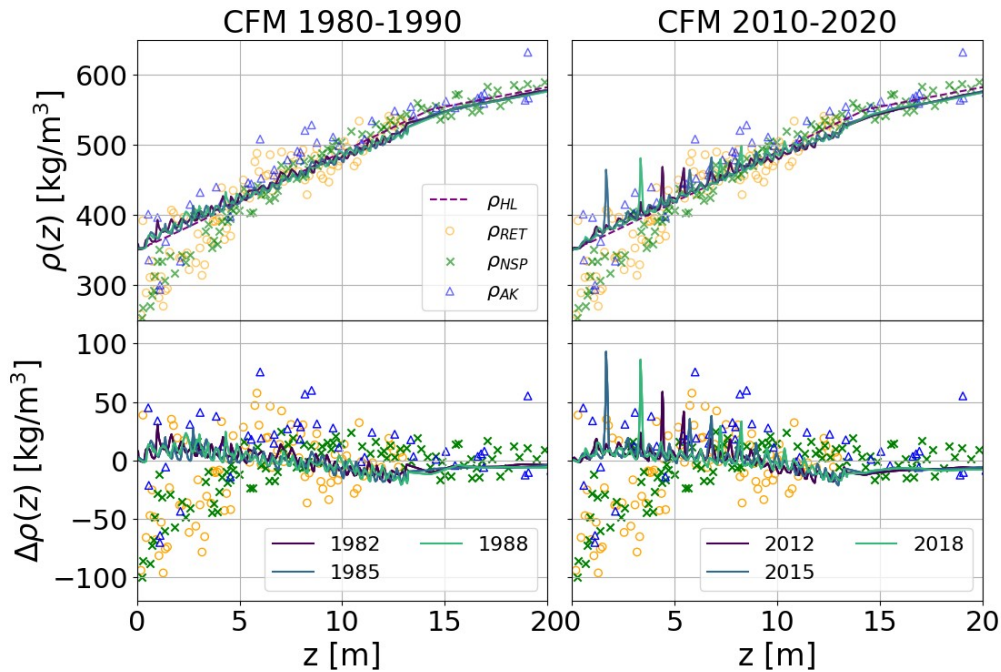


Variable Surface Density ρ_0

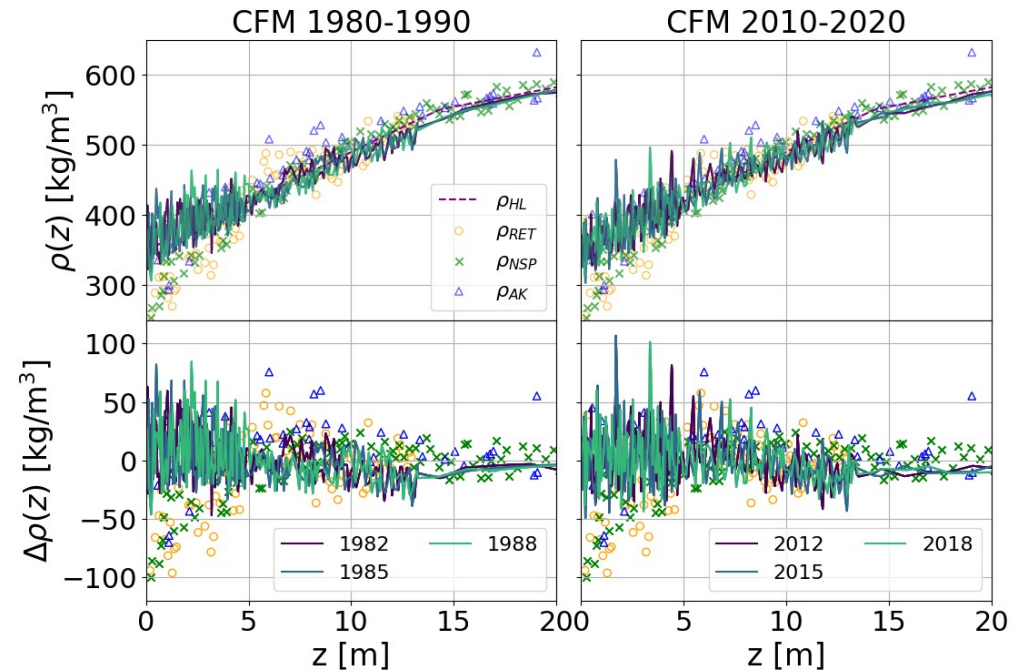


Variable Surface Density ρ_0 - CFM density

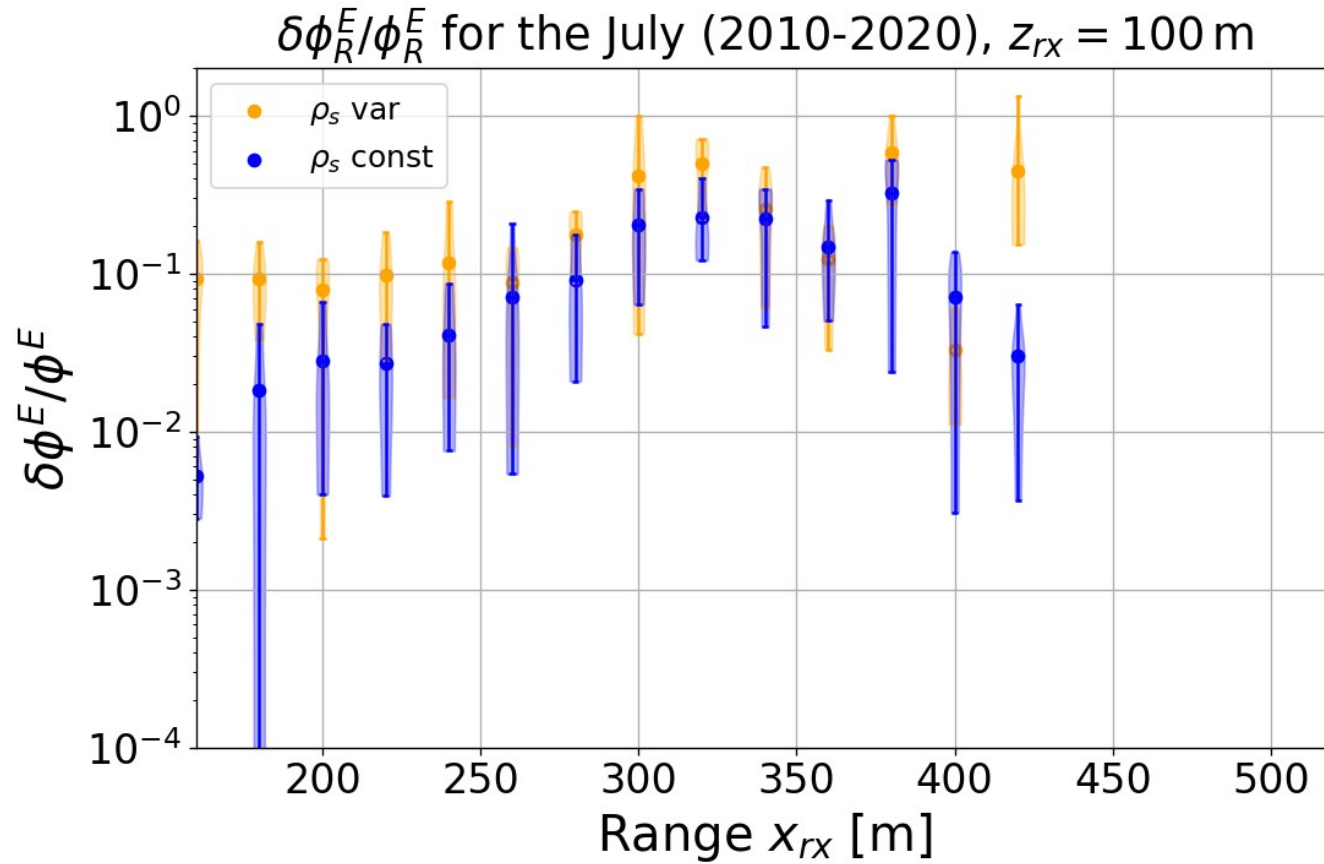
Constant ρ_0



Variable ρ_{0v}

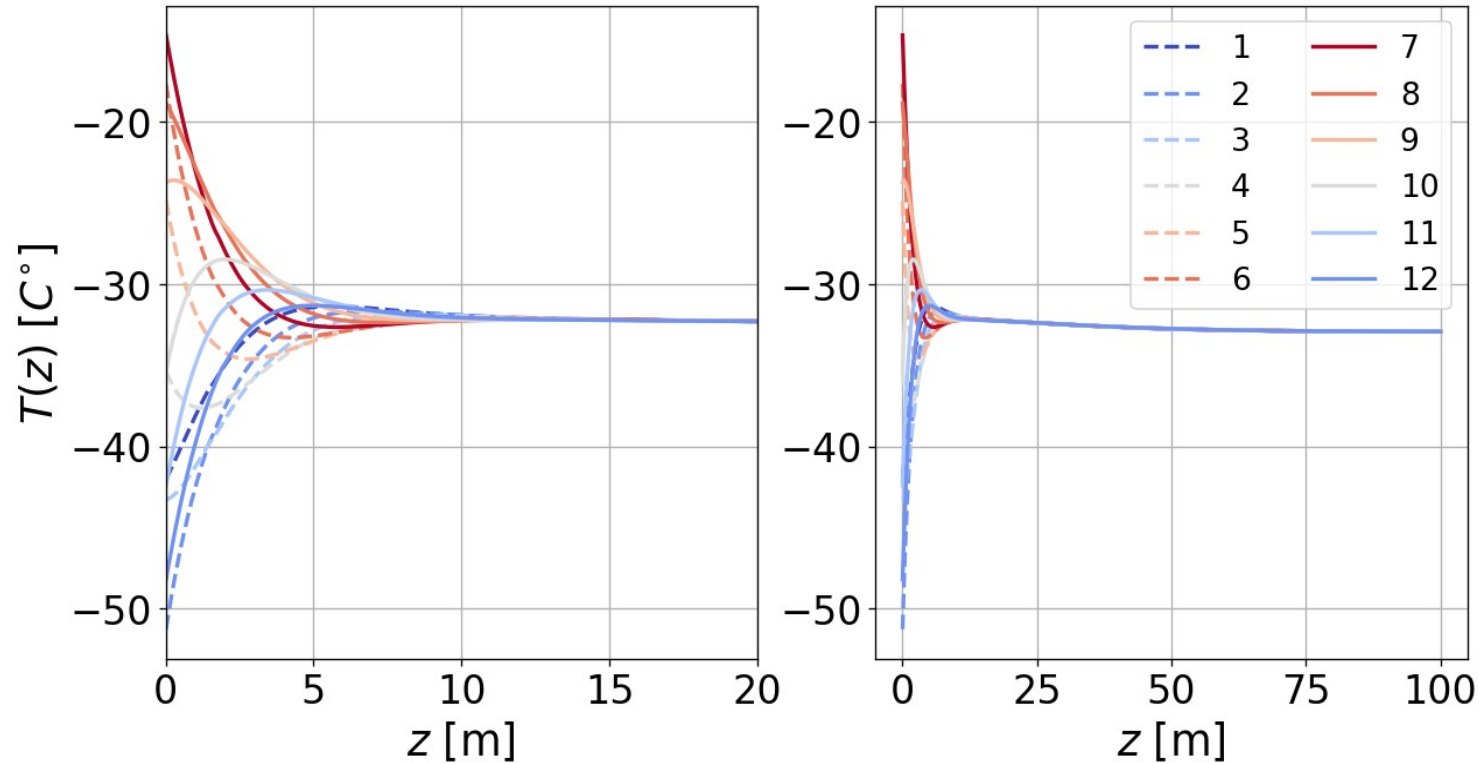


Variable Surface Density ρ_0 - RF Fluence

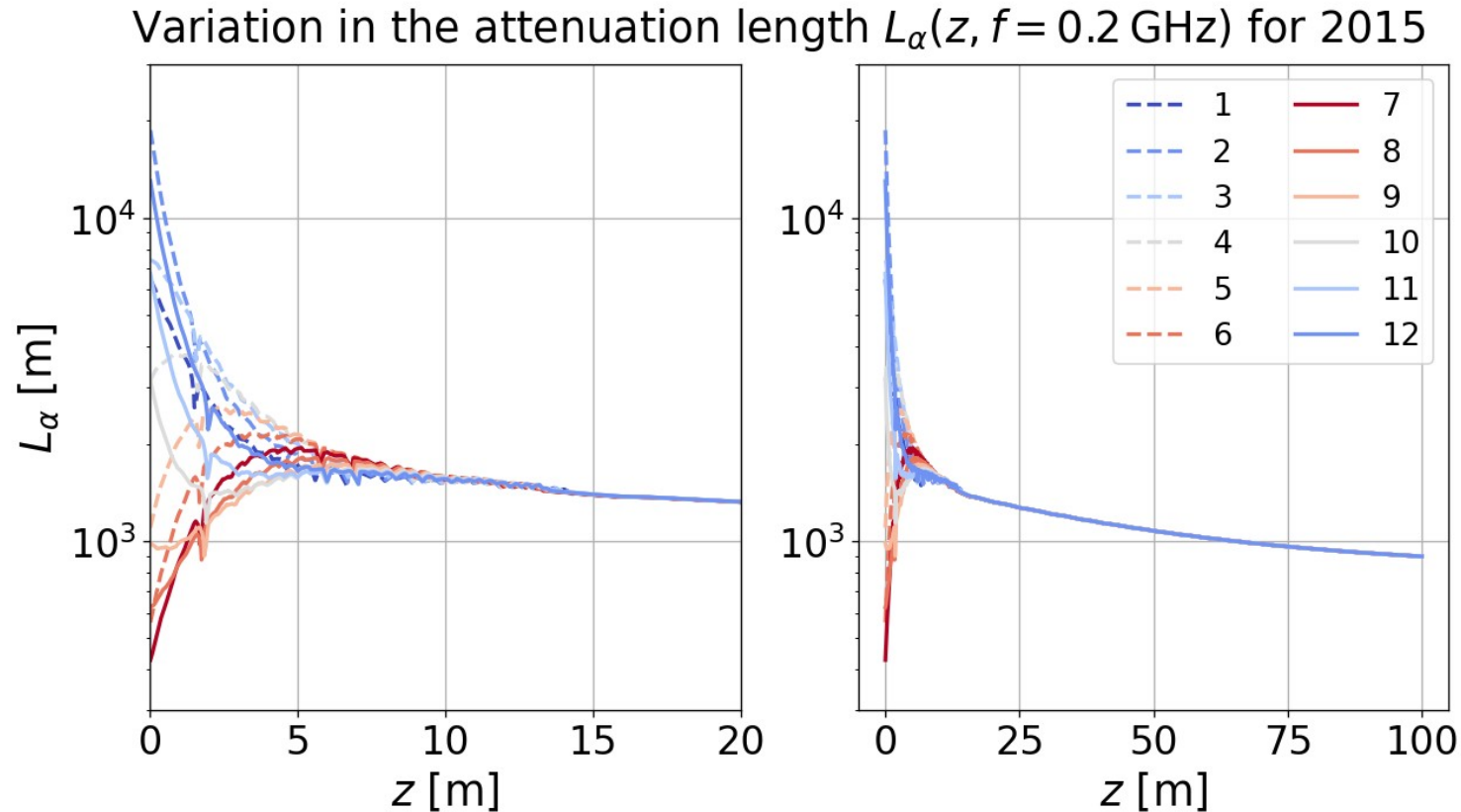


Attenuation variation

Variation in the temperature profile $T(z)$ for 2015



Attenuation variation



Attenuation variation

Attenuation loss η_α variation over 2015

$z_{tx} = 90 \text{ m}$, $z_{rx} = 100 \text{ m}$, $f = 0.2 \text{ GHz}$

