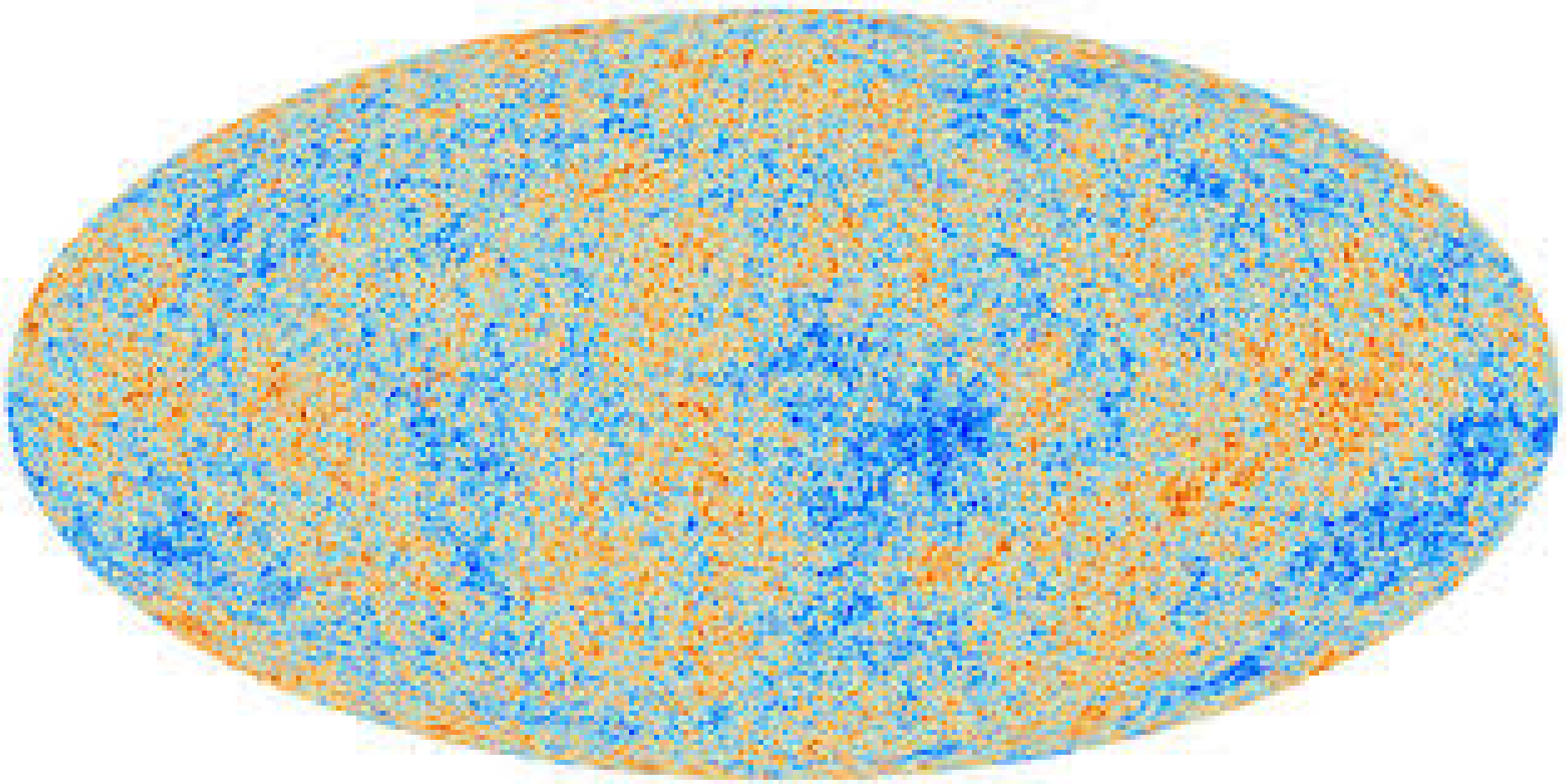
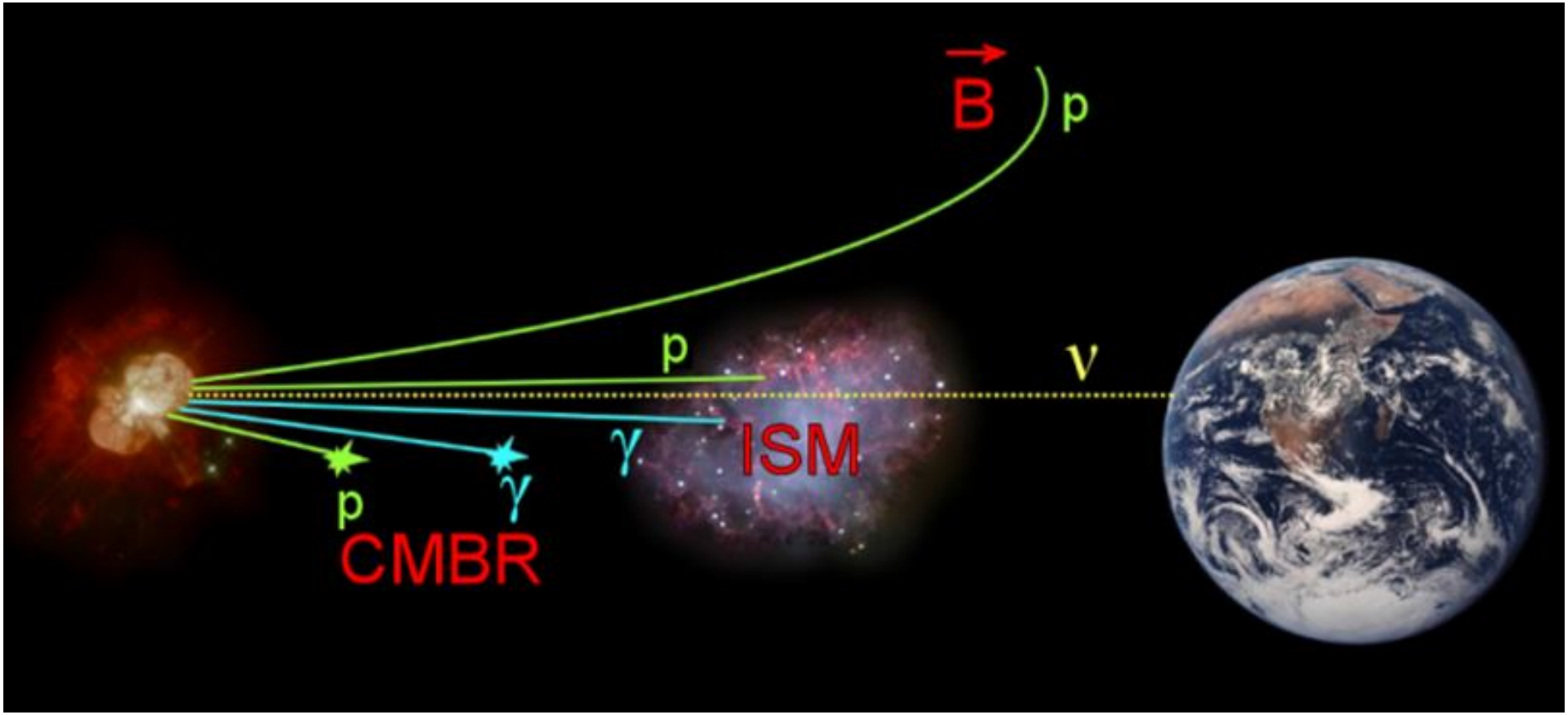
ICE and ASTROPHYSICS

Reminder: What are standard tools of astronomy? (JWST, Hubble, e.g.)

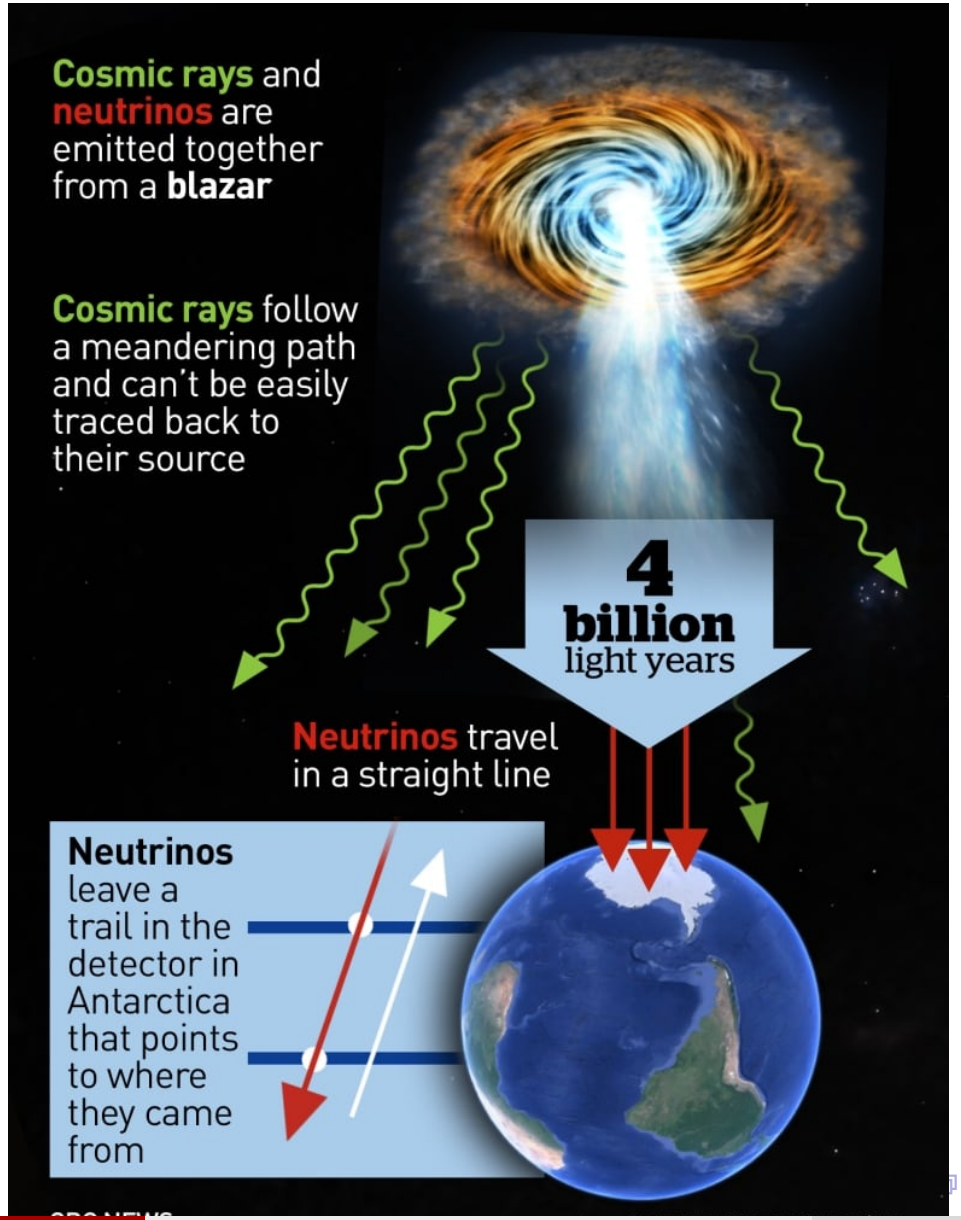
CMB: Limitation to Telescopes (if eyes saw λ=1 mm)



Alternate astronomical tracers



Neutrinos point directly to sources (but rarely interact)

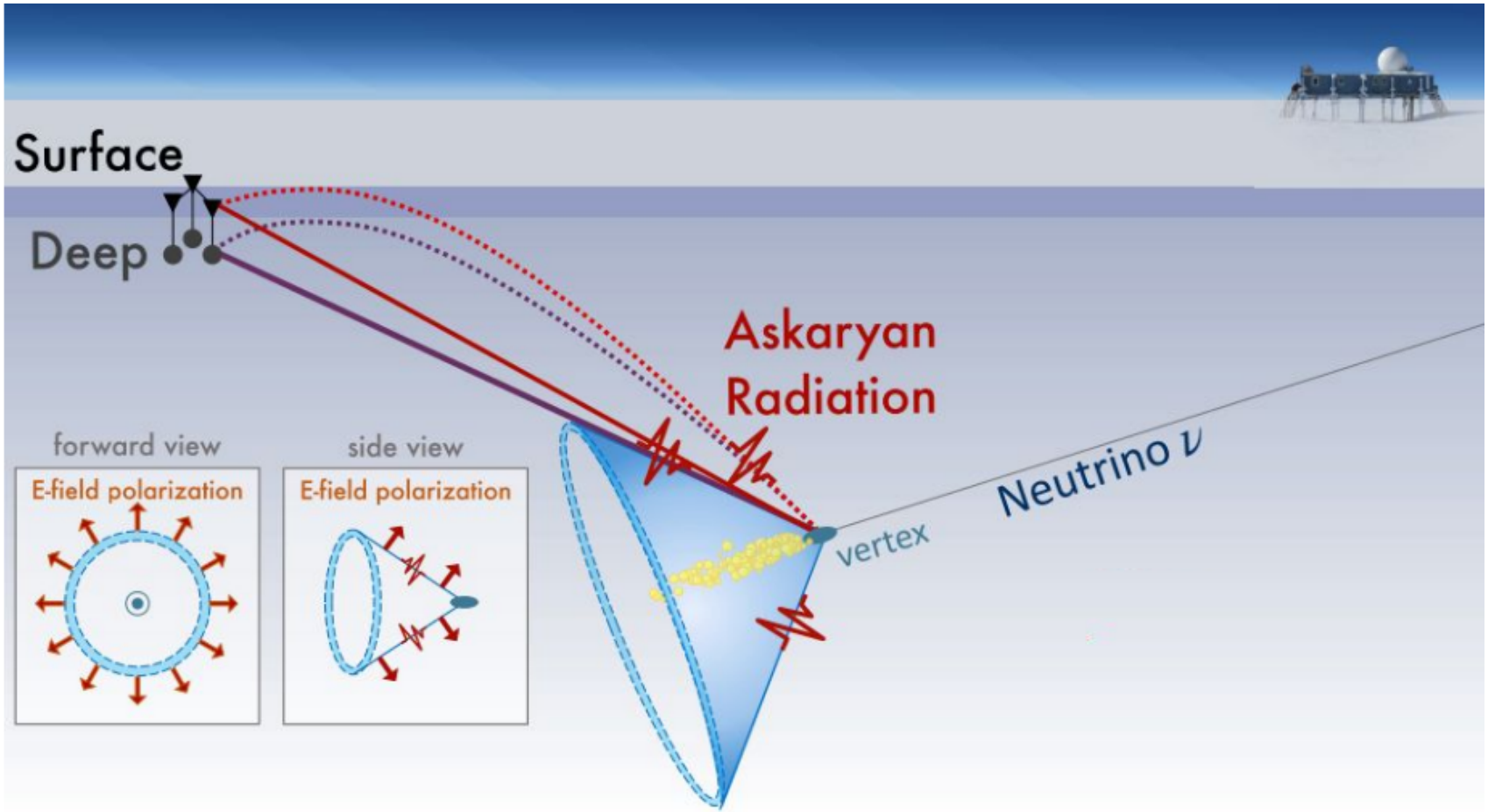


Neutrino factoids

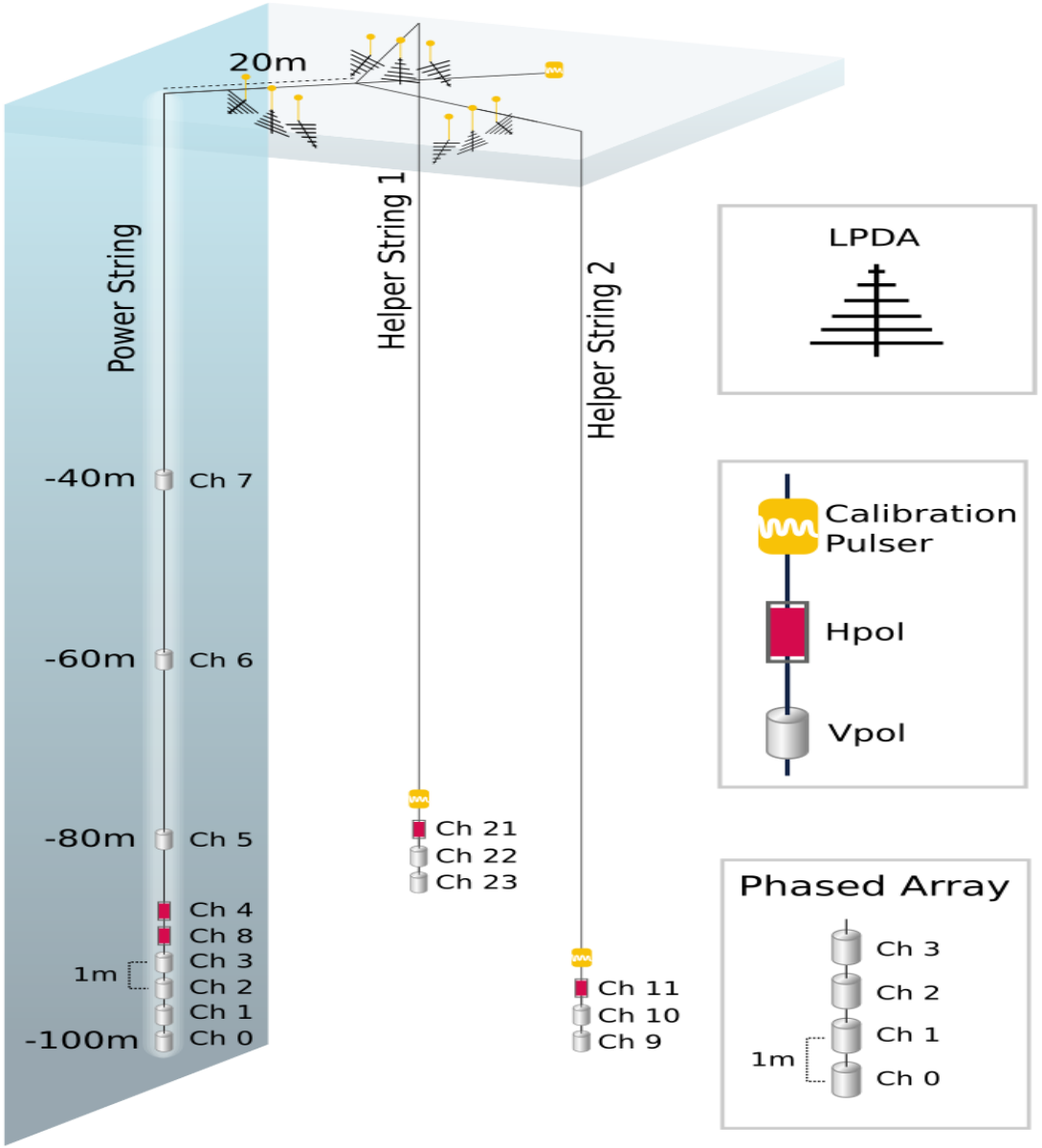
- 300 Big Bang Neutrinos (in addition to 400 CMB photons) per cc
  - each 13.7B yrs old, $E_\nu \sim 1 \rightarrow 100$ μeV
- Solar neutrinos, 50 trillion/body/second.
  - On average, only one will be stopped by biomass per lifetime.
- Aside: ^{40}K neutrinos in salt
  - each person emits 200 million neutrinos per day
- Supernova: Sources of 10^{15} eV neutrinos
- Higher Energies - Gamma-Ray Bursts, Active Galactic Nuclei, 'cosmogenic' neutrinos

Small interaction probability⇒need BIG target transparent to radio waves: Earth icecaps, e.g.
Detect radiowaves from debris following neutrino-ice collision!

Detection Strategy



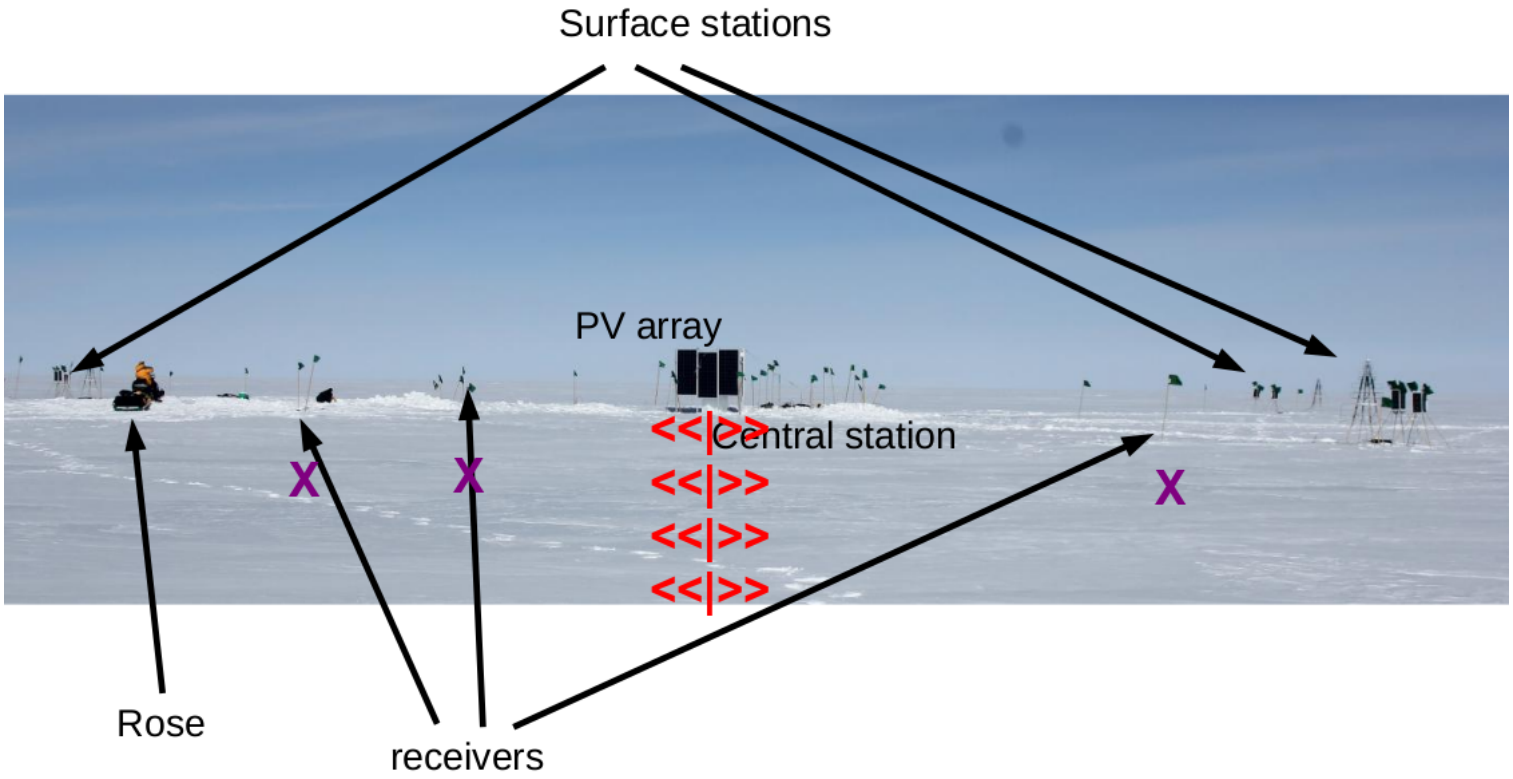
RNO-G (Summit Station, Greenland)



+ High pt. on icesheet
+ well-characterized ice!
+ Less logistically strained than South Pole
- “North Winds”
- It rains!!

Radar Echo Telescope (Summit, Greenland)

Different technology: scan ice with radar!



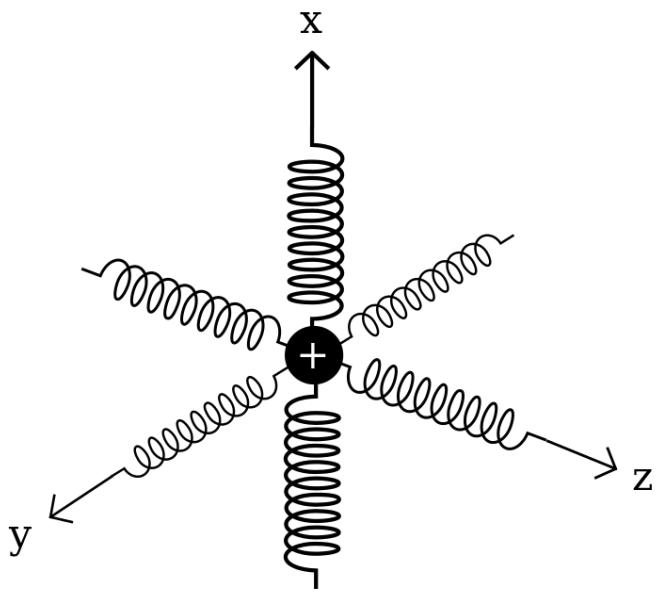
+ Better geometric acceptance!
- New technology

Detection: Pure as the driven snow

From Snow Queen to...

Dielectric permittivity

Qualitatively, dielectric constant ϵ for any material determined by response of electrons in medium to incoming EM radiation fields



- electrons bound to atomic nuclei by Coulomb force ($\sim$spring) in 3-d
- Incoming EM field drives atomic electrons into oscillation
- Re-radiation of field: index of refraction
- Absorbed signal: attenuation
  - Resonance (water in microwave oven, e.g.)
- Asymmetric (non-spherical) response: birefringence

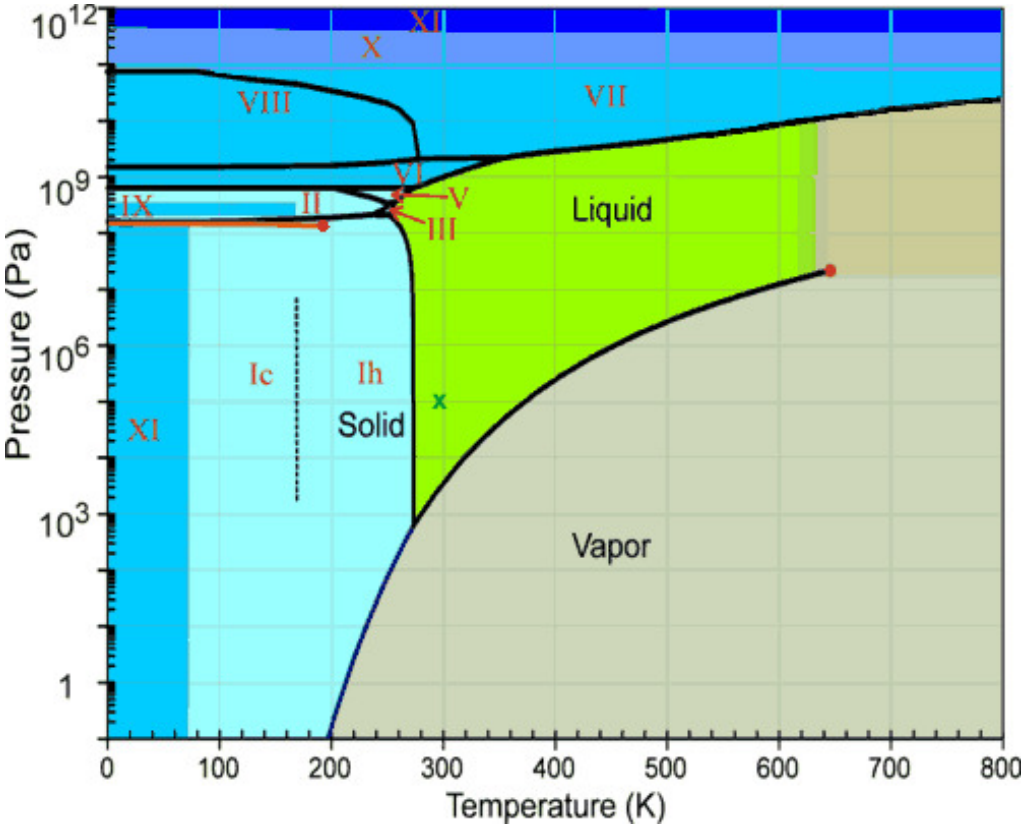
These dielectric properties largely determine ν detection rate.

ICE

- Chemistry: it gets bigger when it freezes!
- Physics: Dielectric stuff you hoped you could forget
  - SP ice .ne. Greenland ice!
- Biology
  - Stuff lives in it in ice cores!
  - Astrobiology: Enceladus?
- Climatology
  - Albedo and Negative feedback
    - Snowball Earth
- Astrophysics
  - Clear at optical and also radio frequencies
  - Ice as a good cosmic-ray target
  - Cosmic-ray collisions with ice molecules visible from km-scale distances

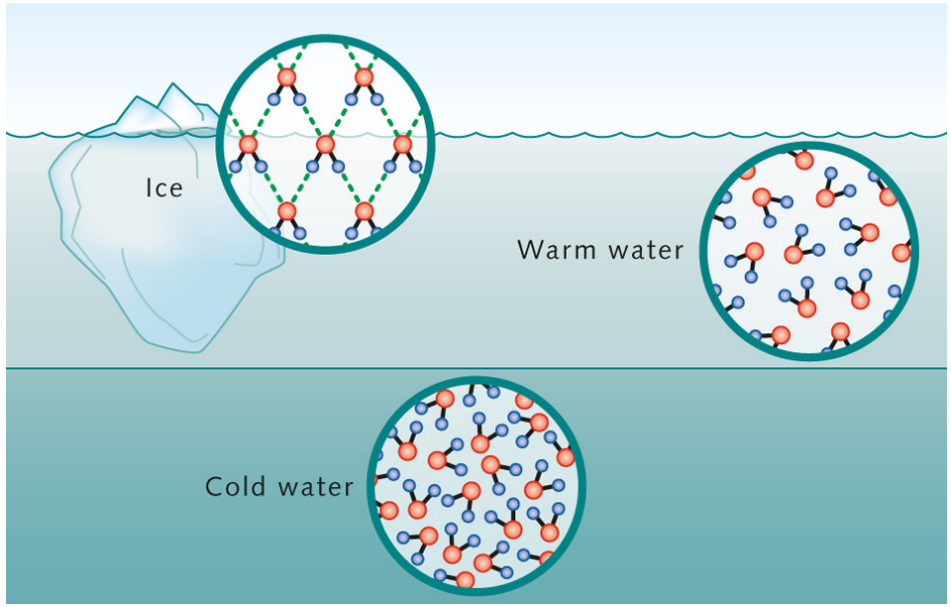
Inupiaq (Alaska) have 100 names for ice!

Chemistry: 18 Shades of Ice



- Terrestrial (familiar) ice: ”Ice 1h”
- 1996: Ice XII discovered
- 2006: Ice XIII and Ice XIV
- 2009: Ice XV found extremely high pressures and 143 C.
  - At P$>1.55\times10^{12}$Pa (10M atm) ice$\rightarrow$metal
- Ice, water, and water vapor coexist at the ‘triple point’: 273.16 K (0.01 C) at P=611.657 Pa.
  - $1^\circ \equiv$1/273.16 of difference b/w triple point and absolute zero (defn as of May 2019)

Oddly, $\rho_{ice} < \rho_{water}$

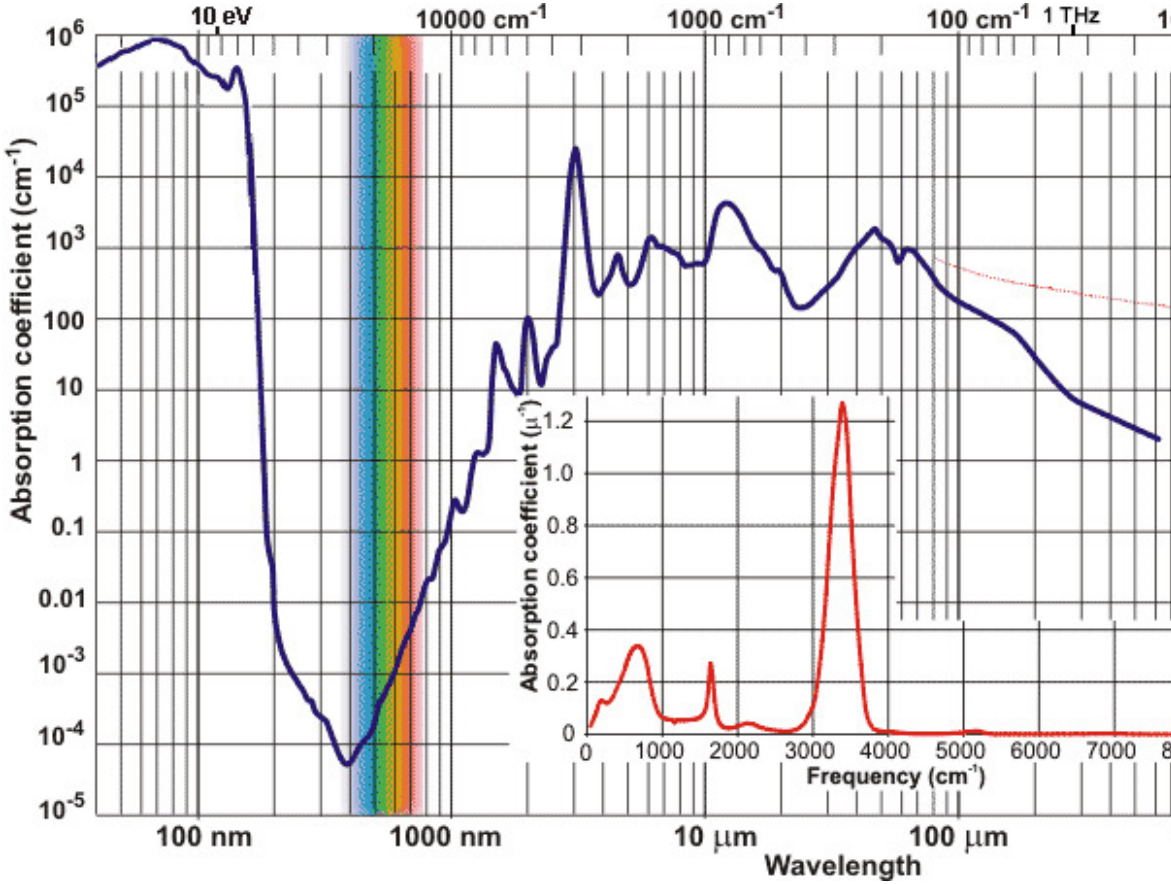


(this happens for Ge, Bi, Si, Pu, liquids that bond into tetrahedrons in solid phase)
(sadly, also for water in cells)

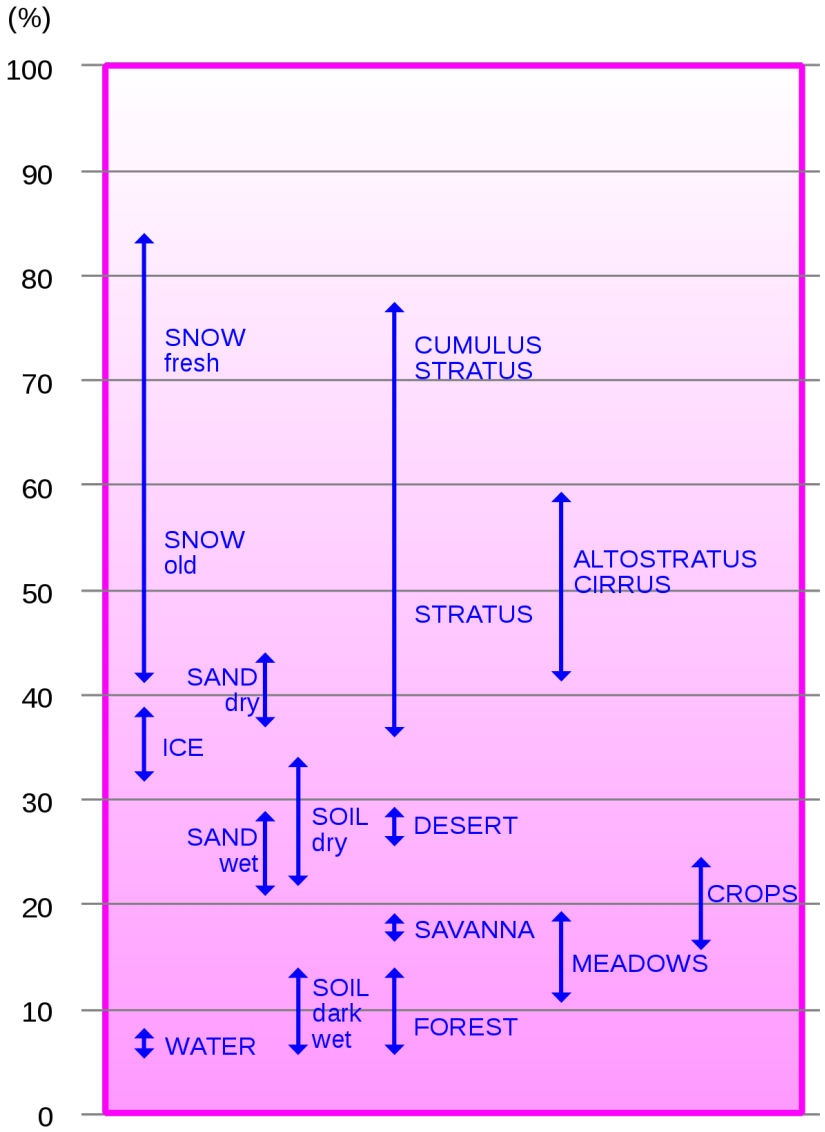
Socio-Cultural impact: Refrigeration, Curling, Marvel's Iceman (2024: new series)

Refrigeration: 400 BC: Persian engineers carve ice in winter and store in 5000 m^3 insulated ('sarooj' - sand, clay, egg whites, lime, goat hair, and ash) caverns in desert during summer

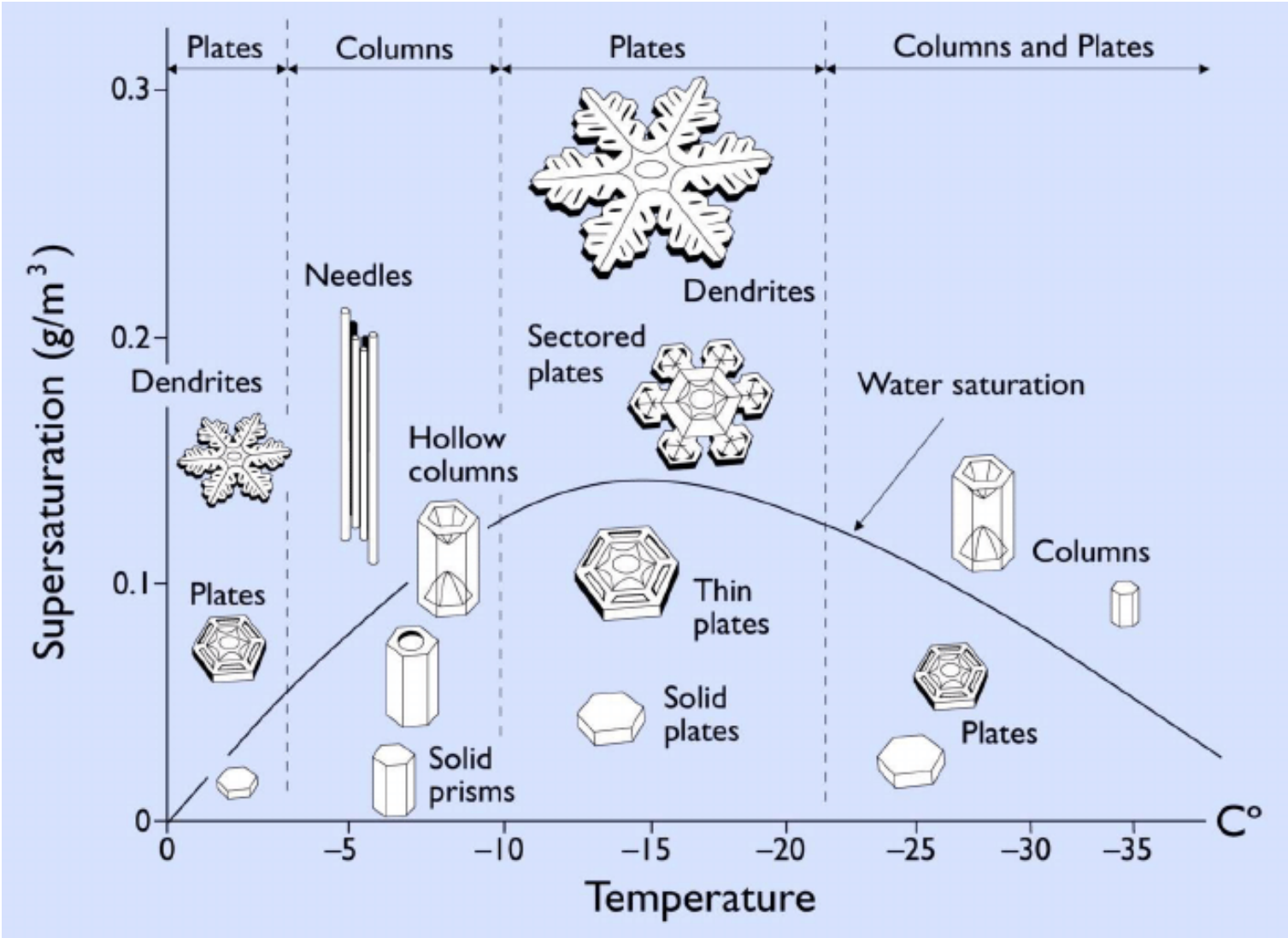
Why is ice bluish? Absorption(λ)



and snow white? Reflectivity and climate



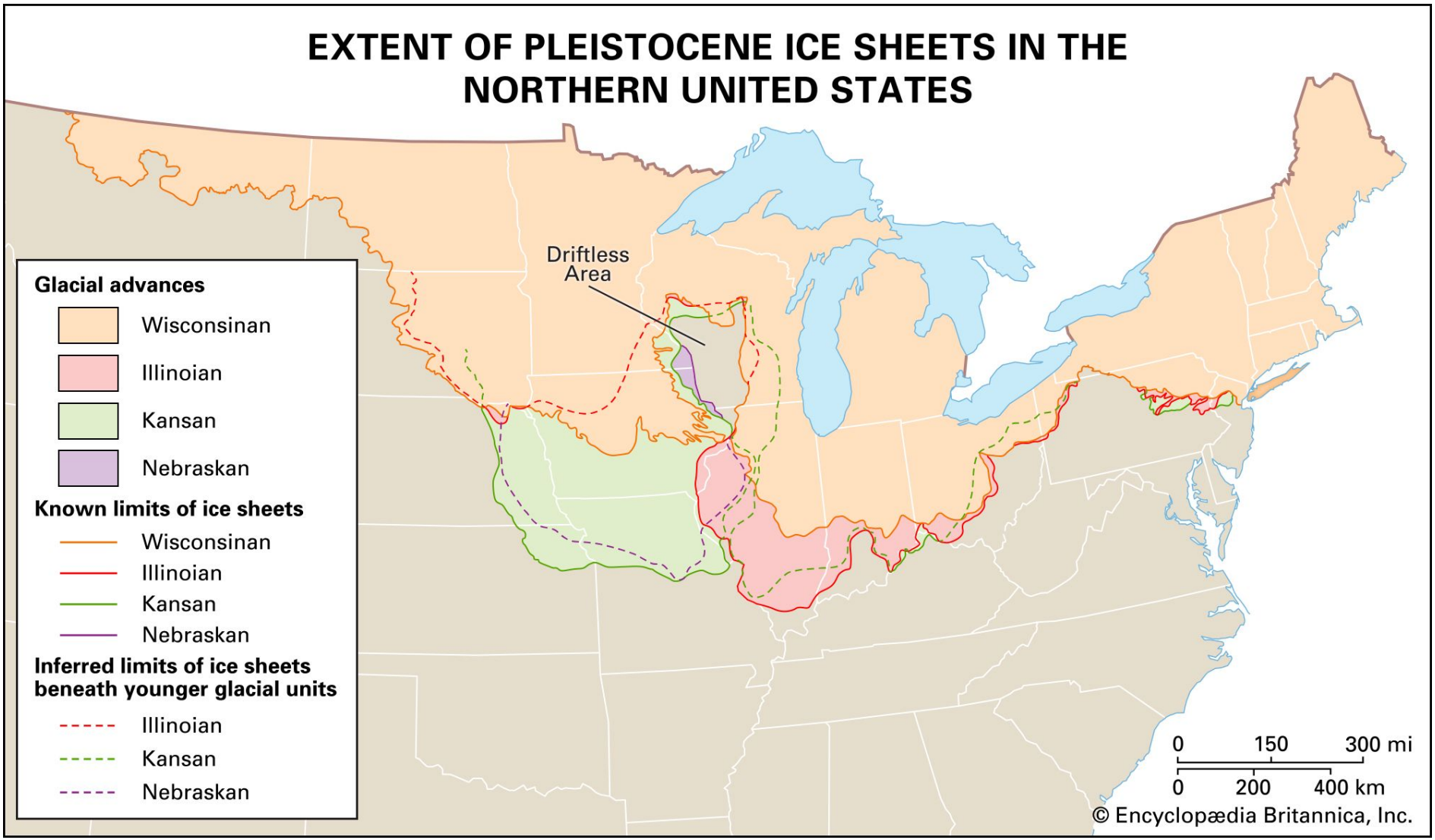
Let it Snow, Let it...



Albedo, ice ages, and the extent of glaciation

- Last glacial max: 20ka
- pre-Illinois glac: 200ka ago

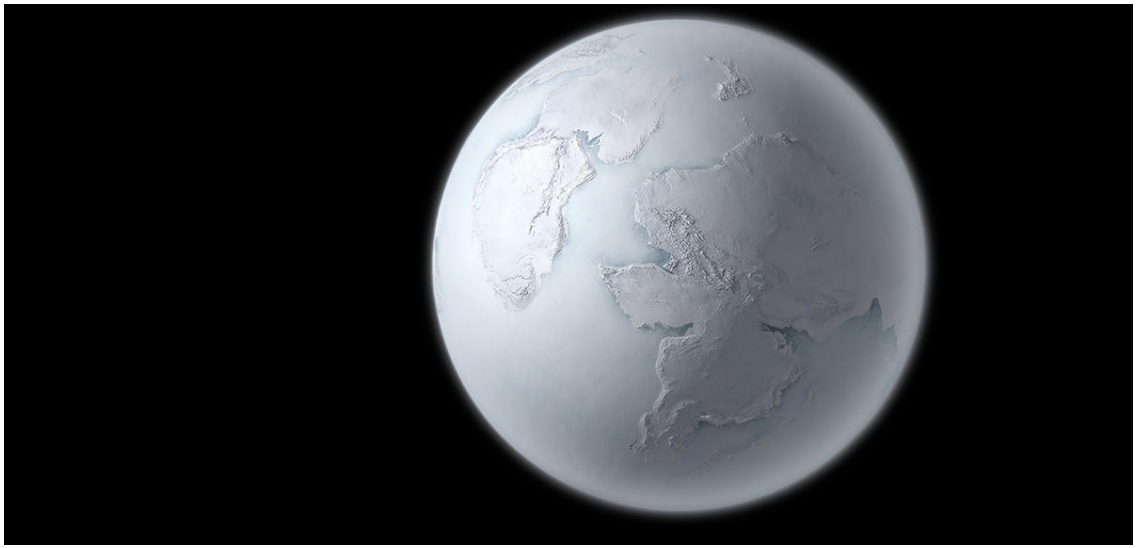
Glaciation, cont



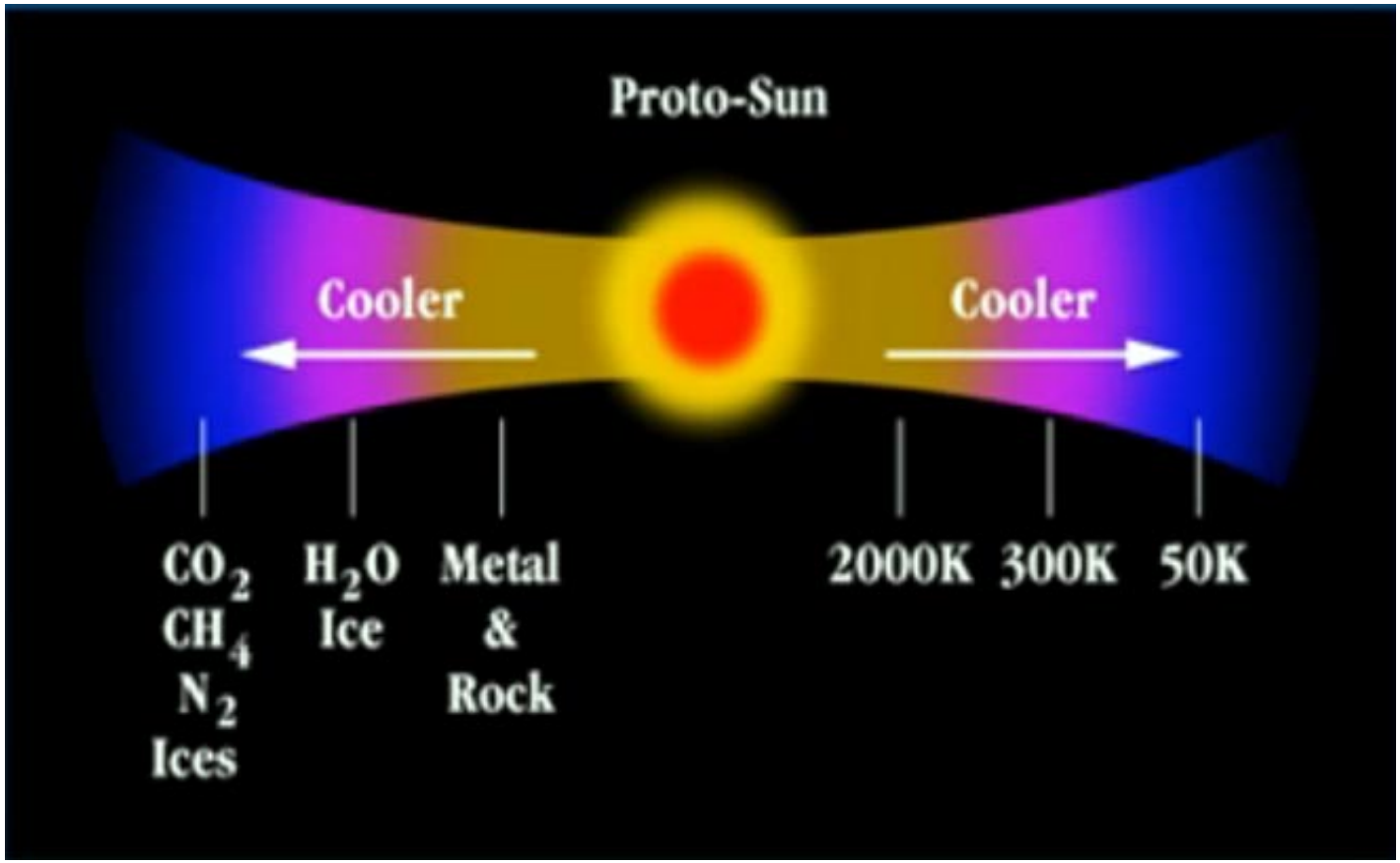
Snowball Earth (750Ma) - but, how?

One hypothesis (based on evidence that CO_2 concentration precipitously dropped at that time):

- Following pangea break-up, more 'interior' acid rain exposes basalt rocks
  - Basalt$\Rightarrow$Major CO_2 sink
  - Cooling + increased glaciation at Poles$\Rightarrow$cooling due to lack of greenhouse gases$\Rightarrow$ $albedo \uparrow \Rightarrow$ $cooling \uparrow$

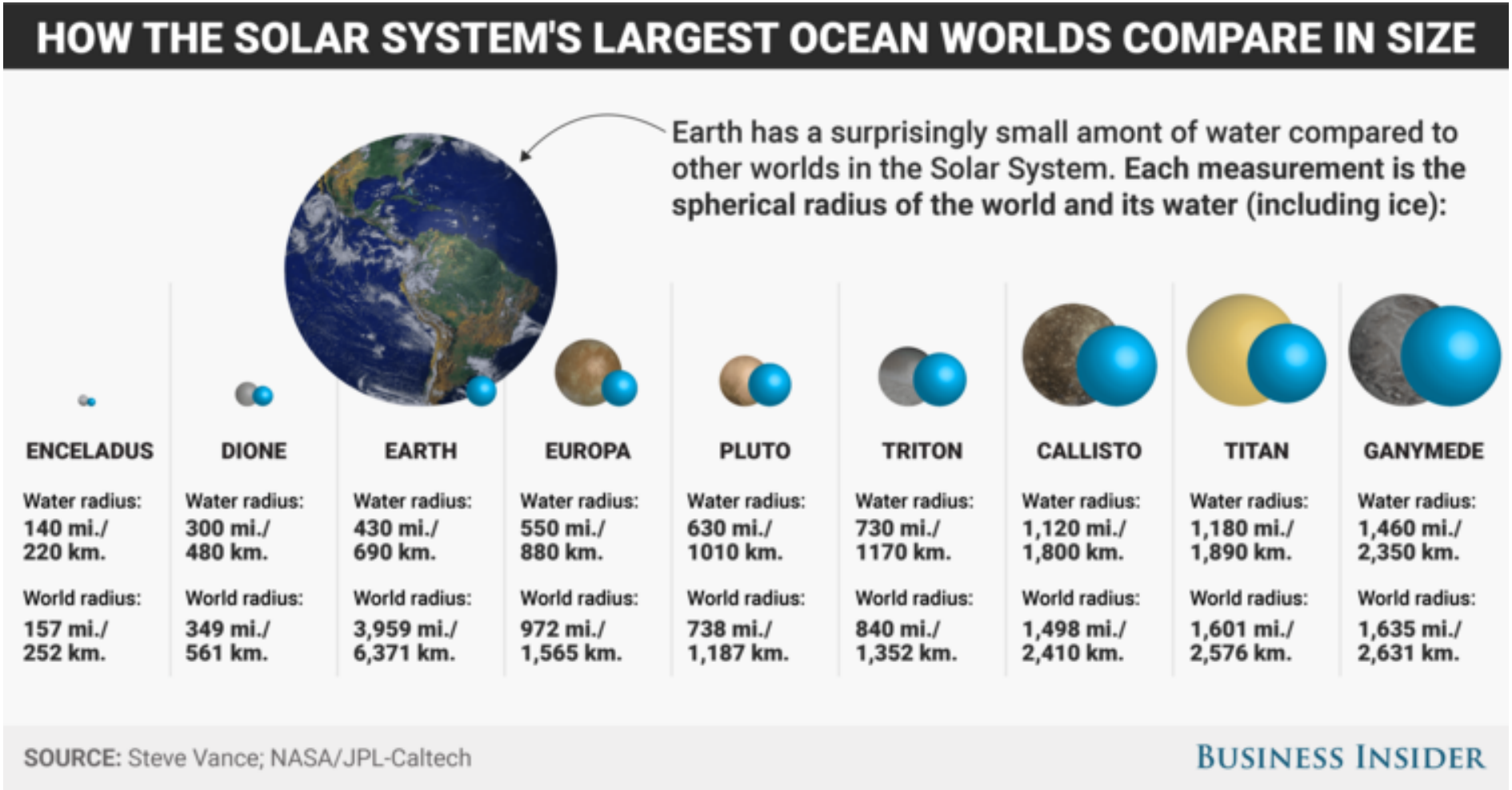


Ice is everywhere in Solar System



Earth water/ice Likely NOT from comets - D:H higher $\times 2$ for comets. pre-existing - possibly locked below surface and released from below (water vapor during volcanic eruptions, e.g.)

Earth has (only) some water



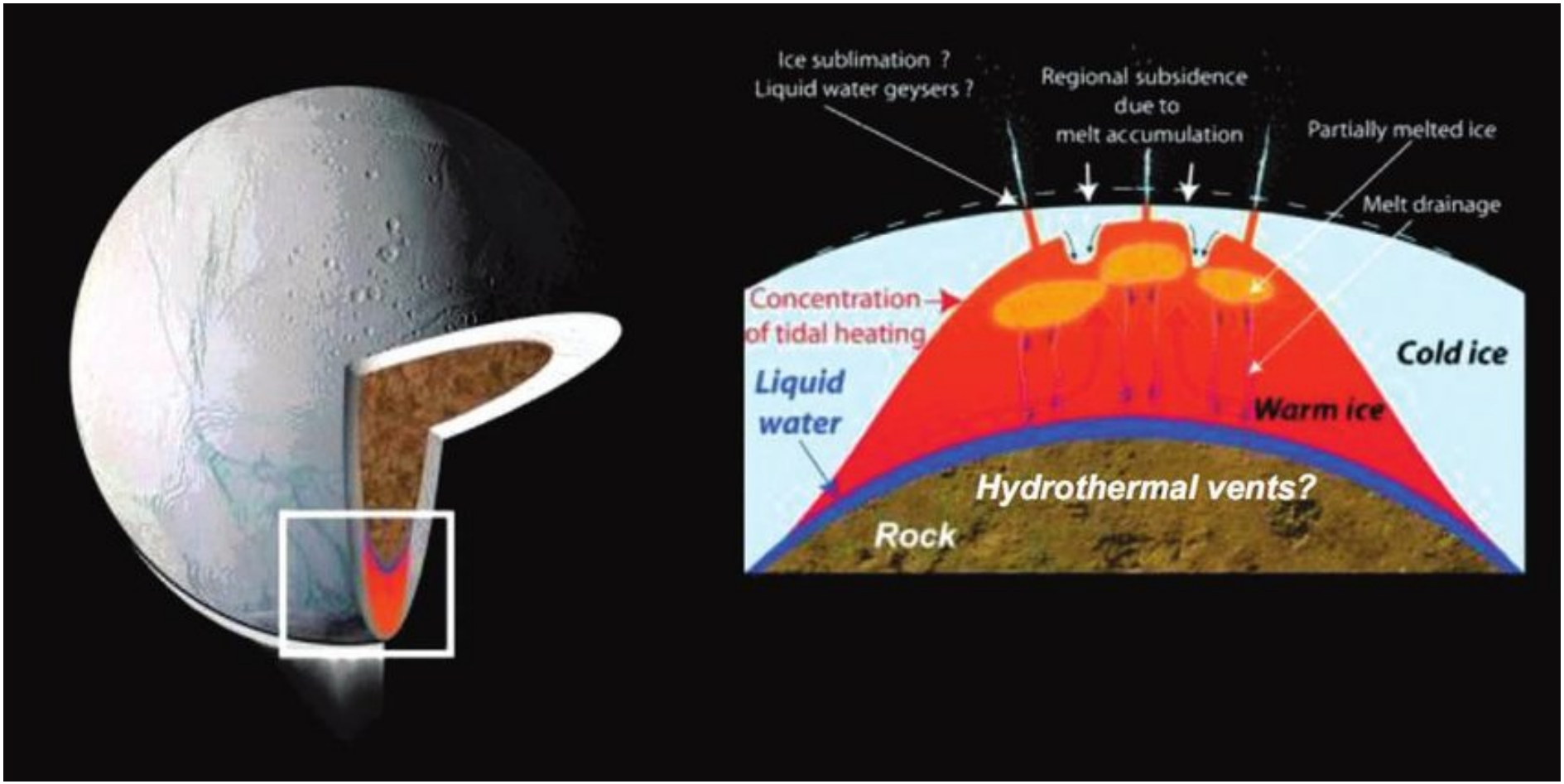
Europa: 2× Earth water

Ganymede: 39×Earth water

Enceladus: 10-50 km thick ice crust over water

speculate life in water below ice crust...

Enceladus XSect



Subglacial Antarctic Lakes Scientific Access (e.g)

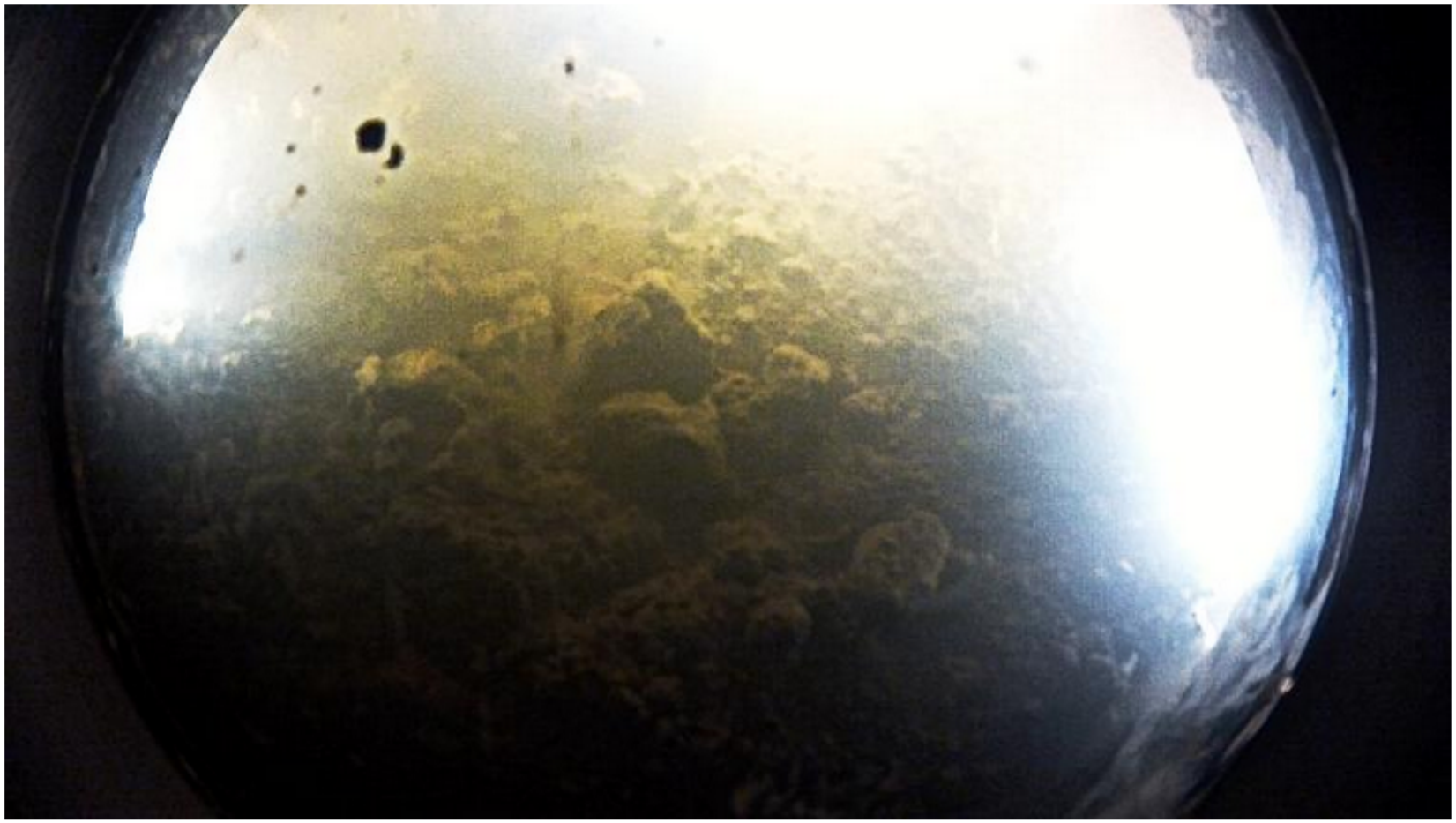
https://salsa-antarctica.org/
Retrieve 1067 m deep sample from Mercer Sub-glacial lake 500 km from SP!

NEWS · 18 JANUARY 2019

EXCLUSIVE: Tiny animal carcasses found in buried Antarctic lake

The surprise discovery of ancient crustaceans and a tardigrade emerged from a rare mission to drill into a lake sealed off by a kilometre of ice.

Life traces @z=-1 km

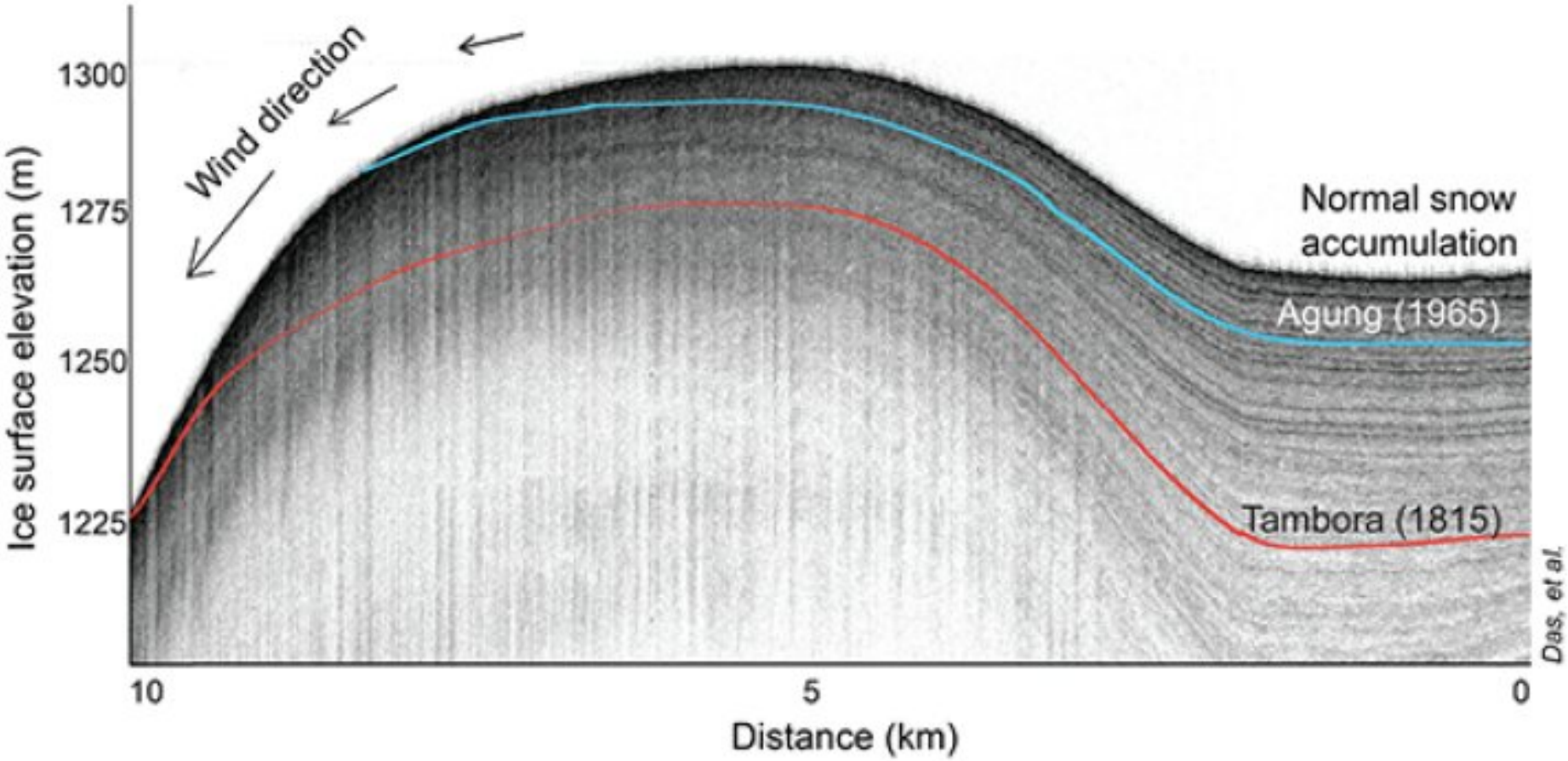


Sediments crumble as an underwater camera touches the bottom of Whillans Lake in Antarctica.

IMAGE COURTESY ALBERTO BEHAR, JPL/ASU, AND NSF/NASA

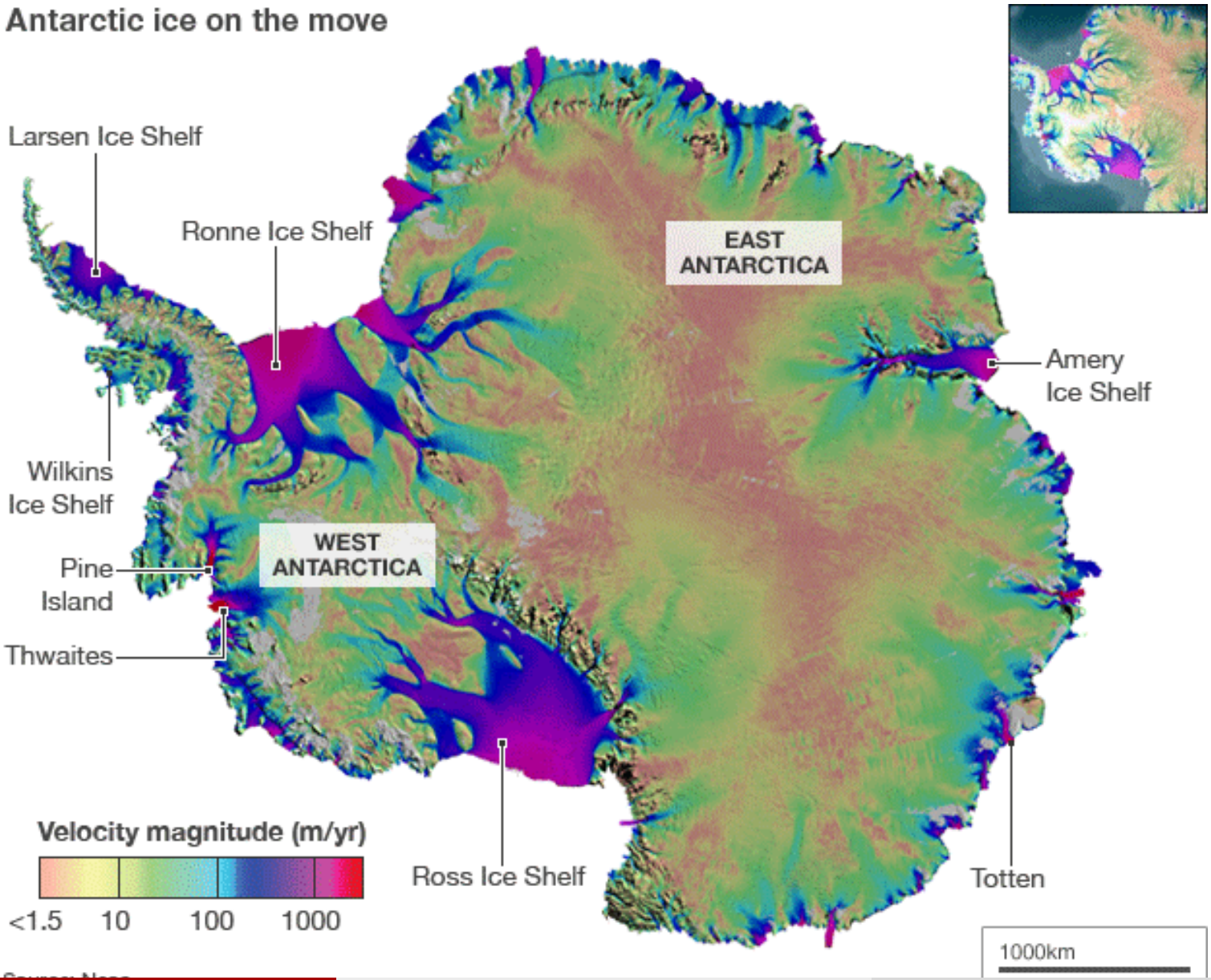
Ice Cores and (fuzzy) WAIS psychrophiles

Ice layers chronicle CO_2 & Volcanoes

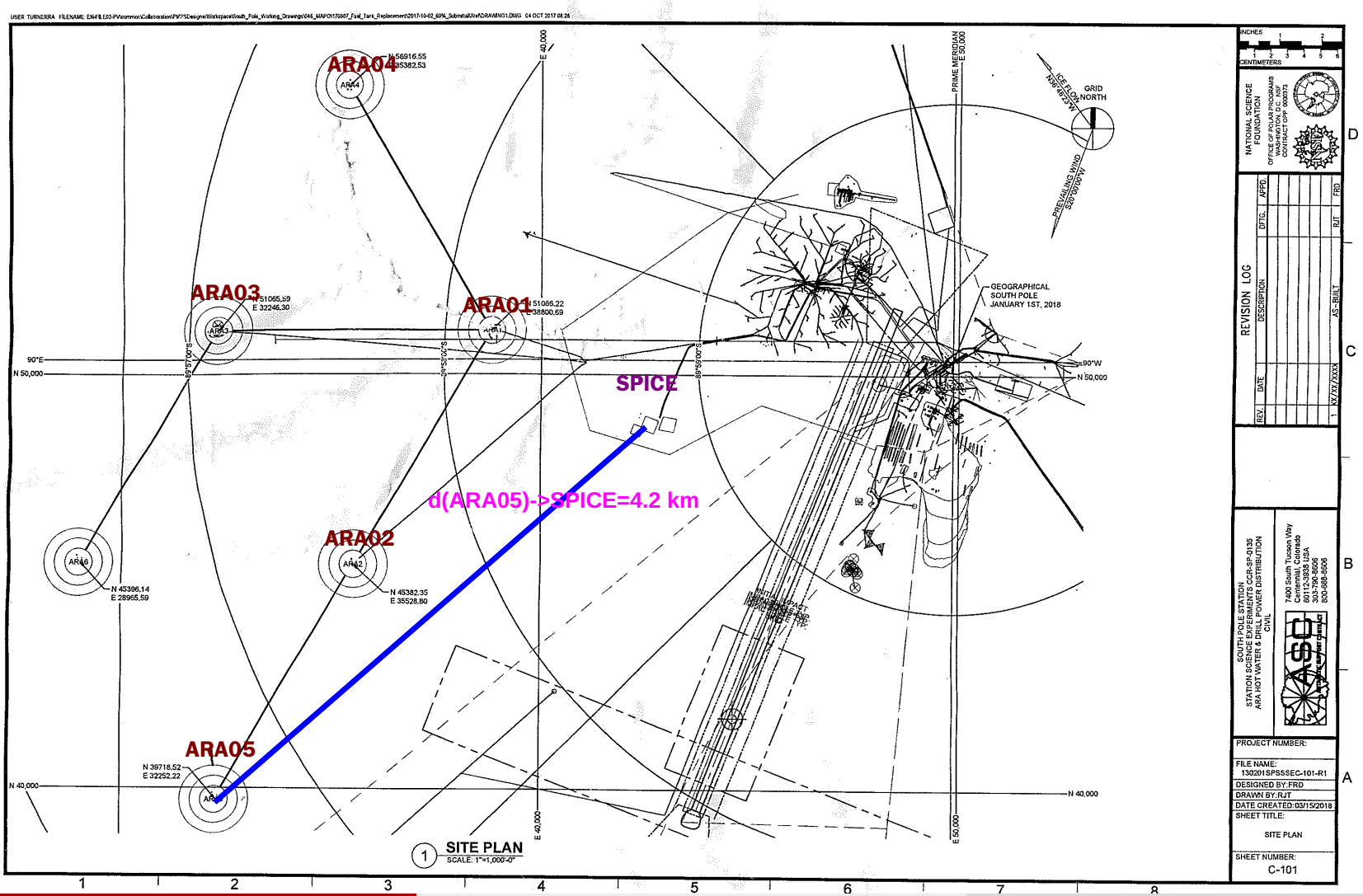


Ice Likes to Move

Some Ice Likes to Move Fast



Ice transports radio waves



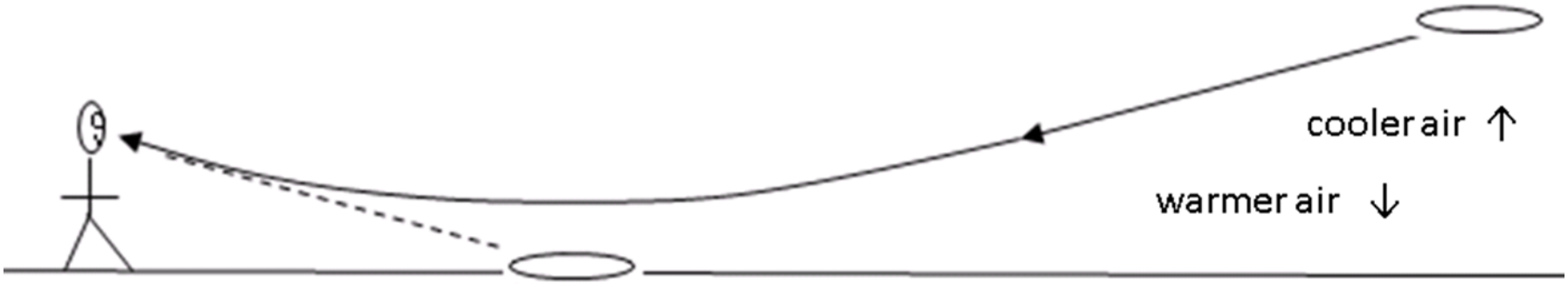
12/18 Test Ice as a CR target medium: Re(ϵ_{ice})⇒'horizon', Im(ϵ_{ice})⇒ L_{atten}

The SPICE core ice-hole

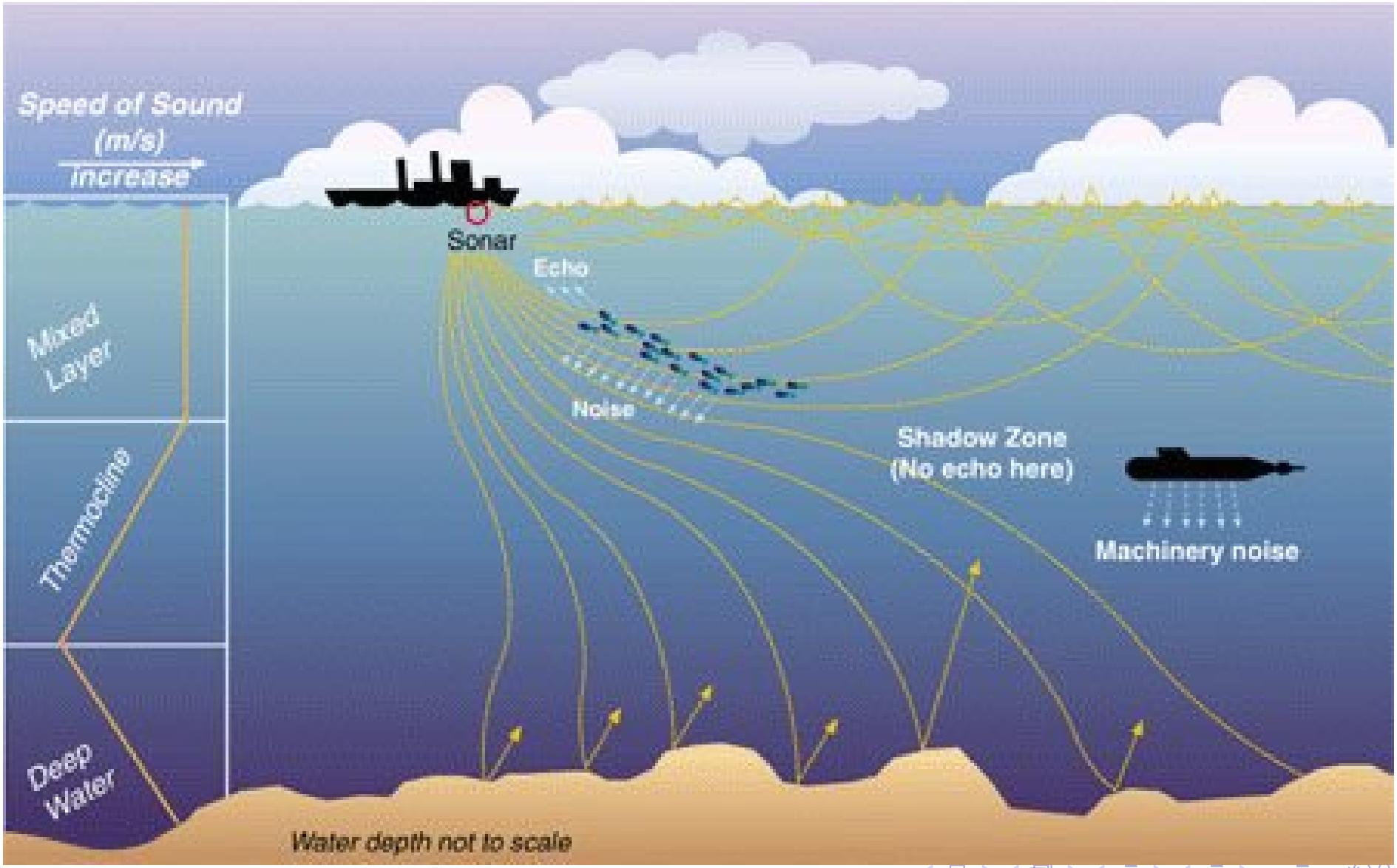
View of South Pole Station from SPICE core site

Double pulses and the mirage effect

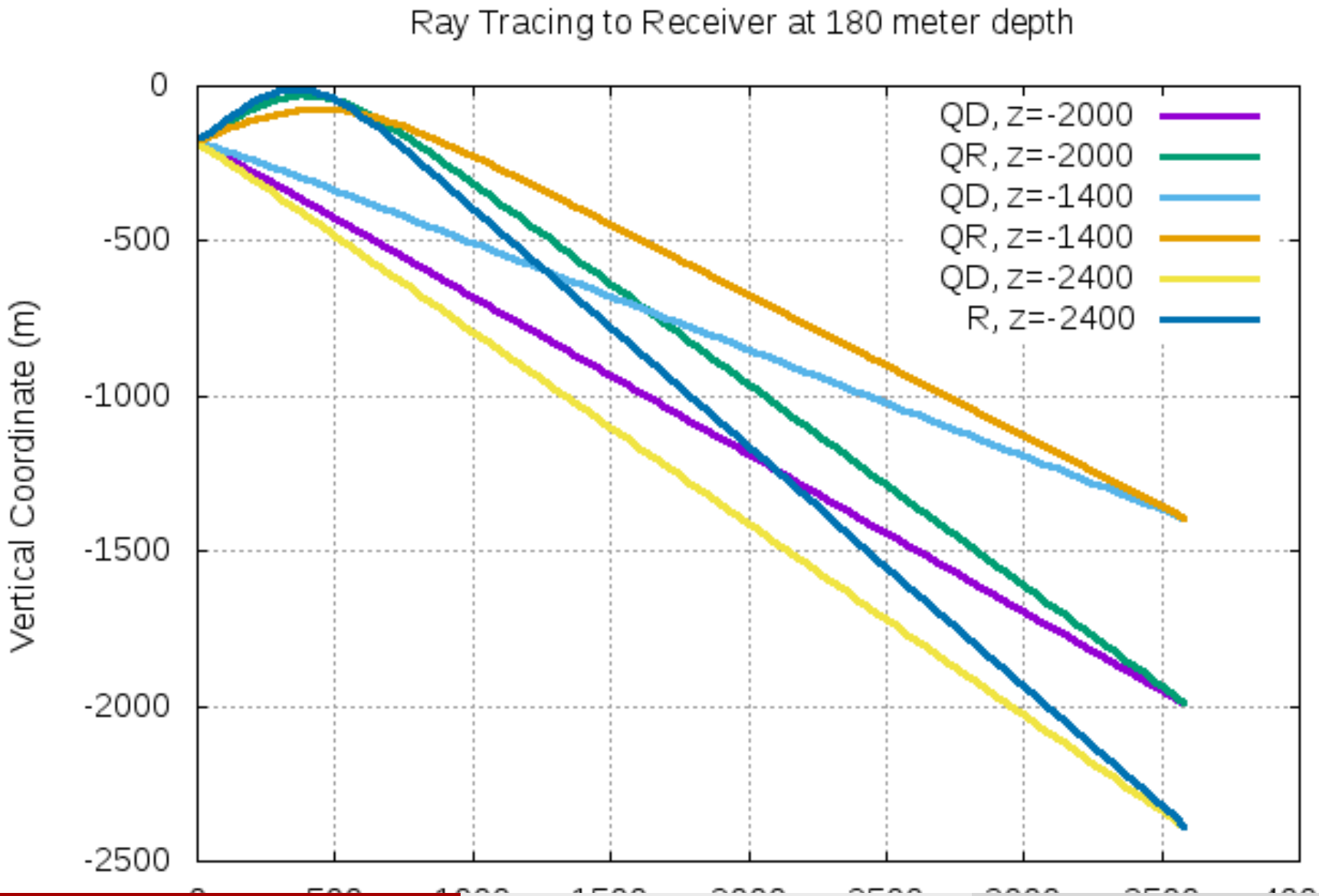
Double pulses and mirages



Curved Signal paths owing to velocity gradient!



Double pulses and the mirage effect



(Coolest ever) example-Huygens construction

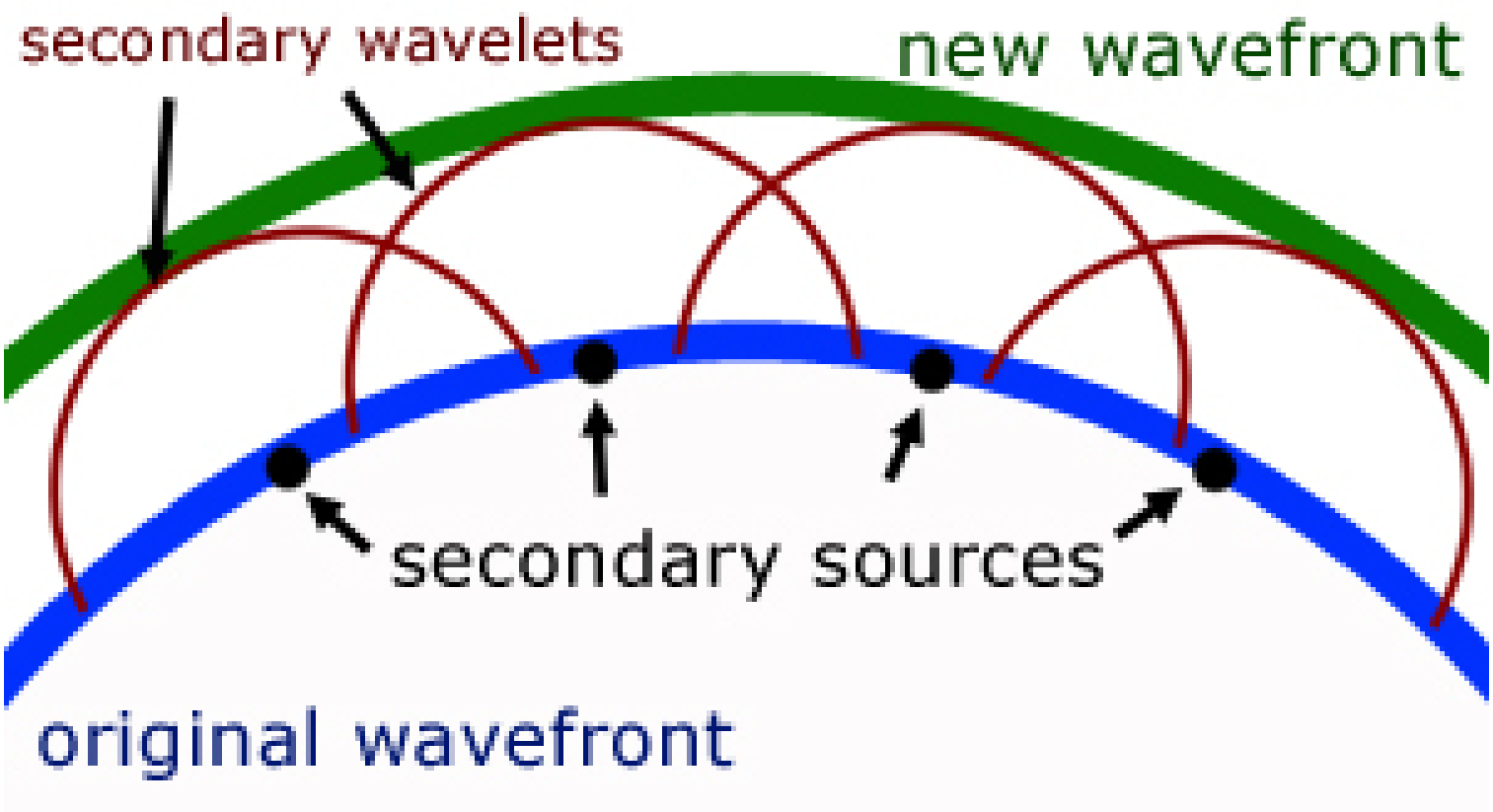
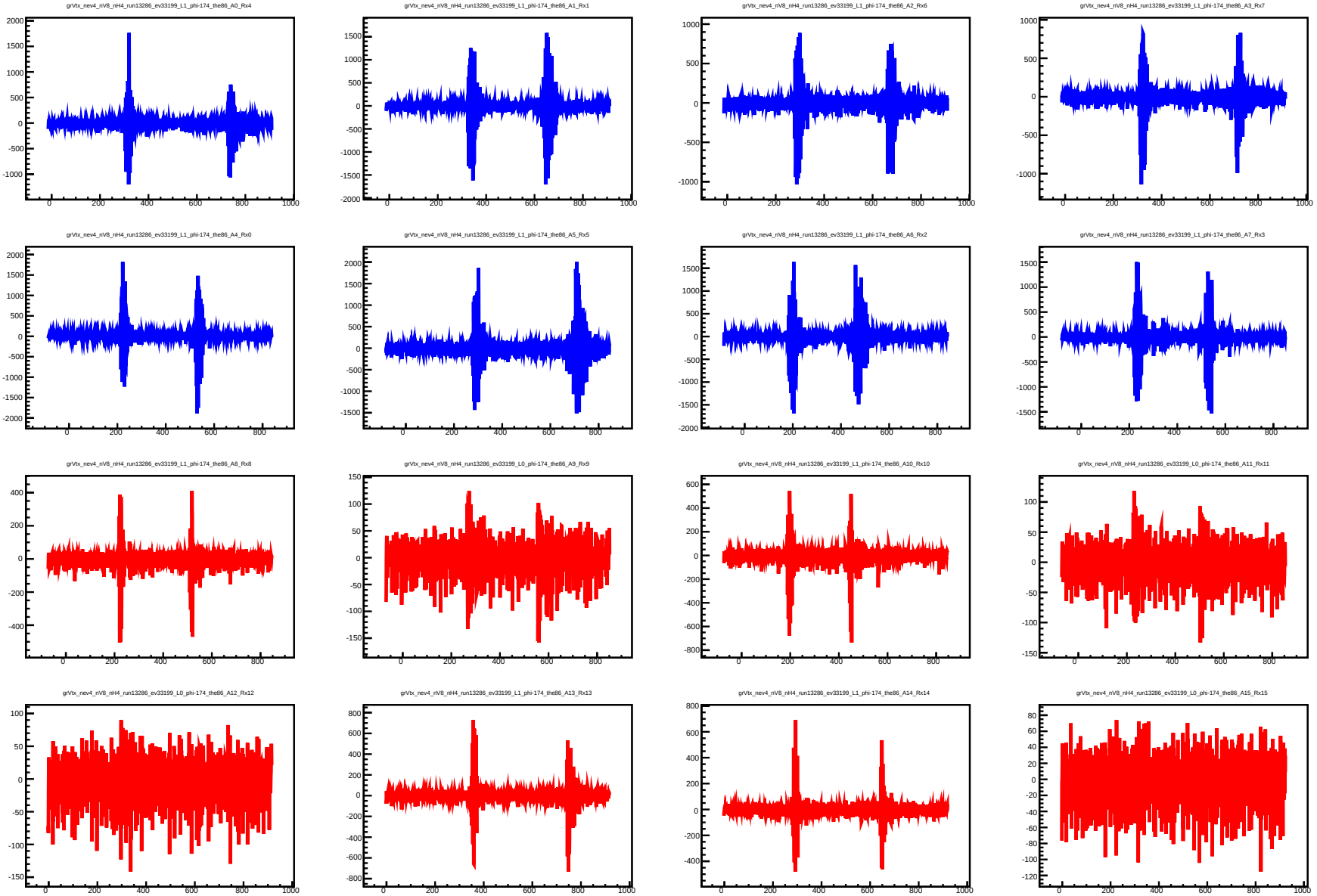


Figure: Huygens Construction/Feynman Path Integral

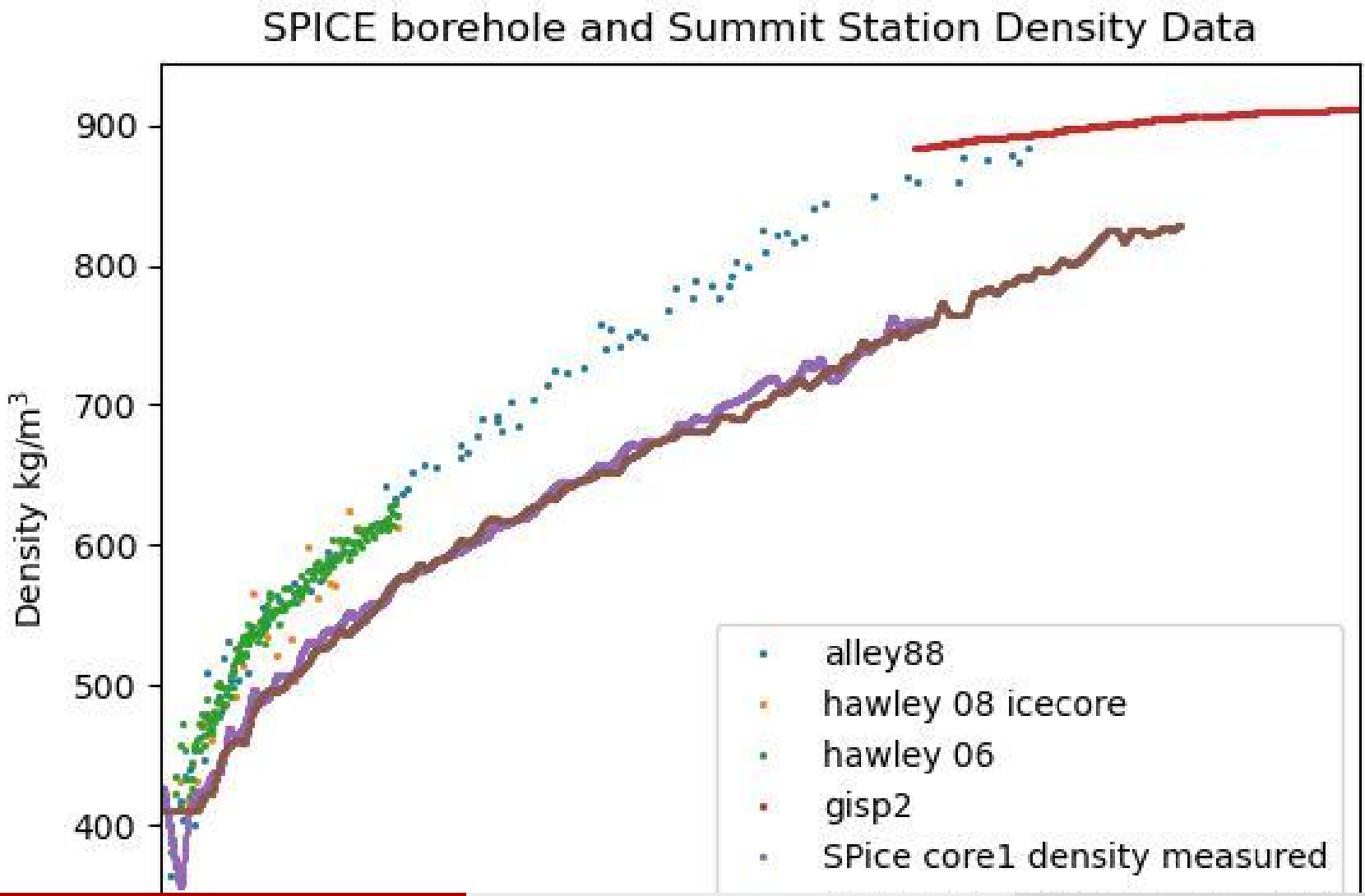
Suppose waveparticle

electron waves propagates like Huygens wavelets
Particle “path” is the one for which waves interfere constructively
“Principle of Least Action”⇔Fermat’s Least Time Principle

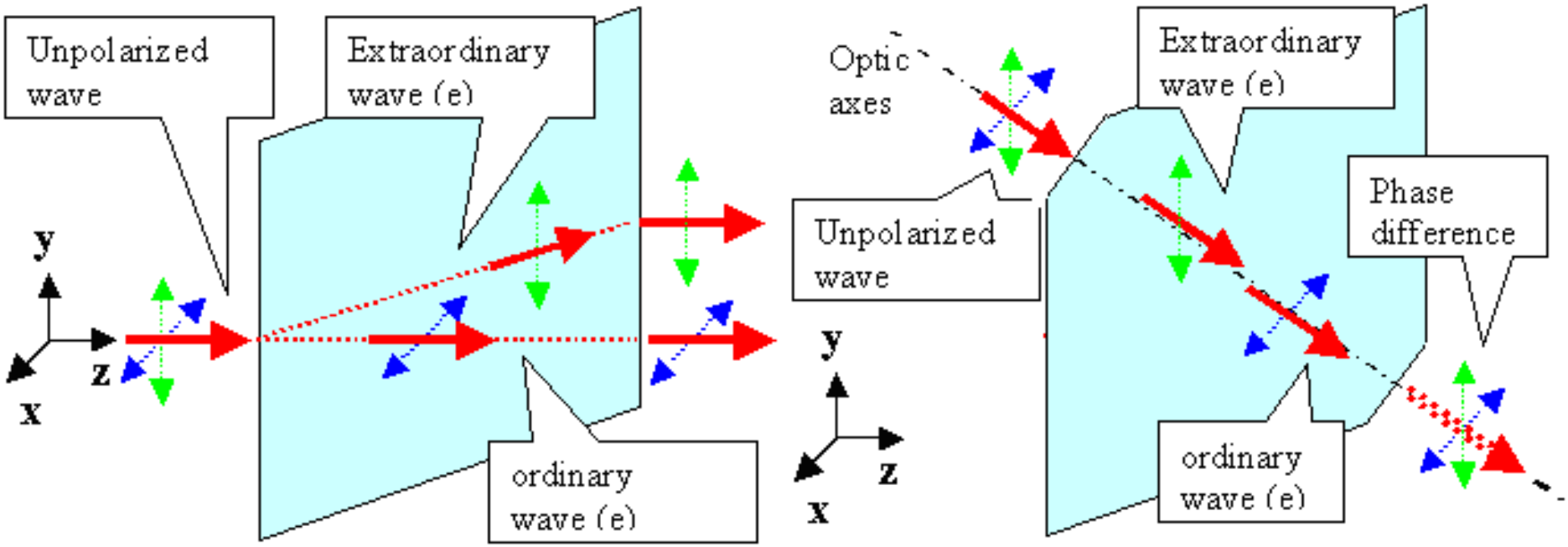
ARA registered signals



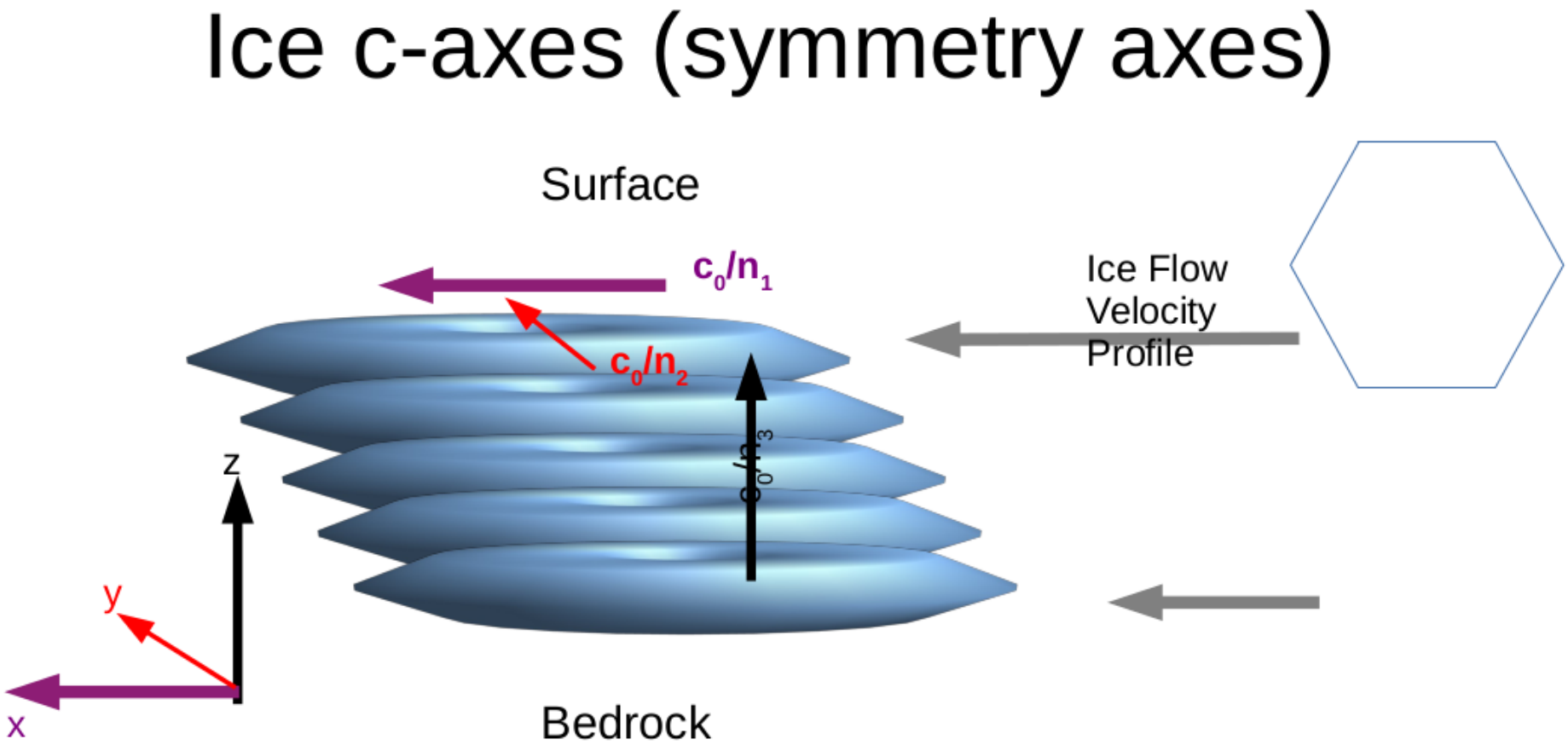
n(z) profile (https://arxiv.org/pdf/2406.00857)



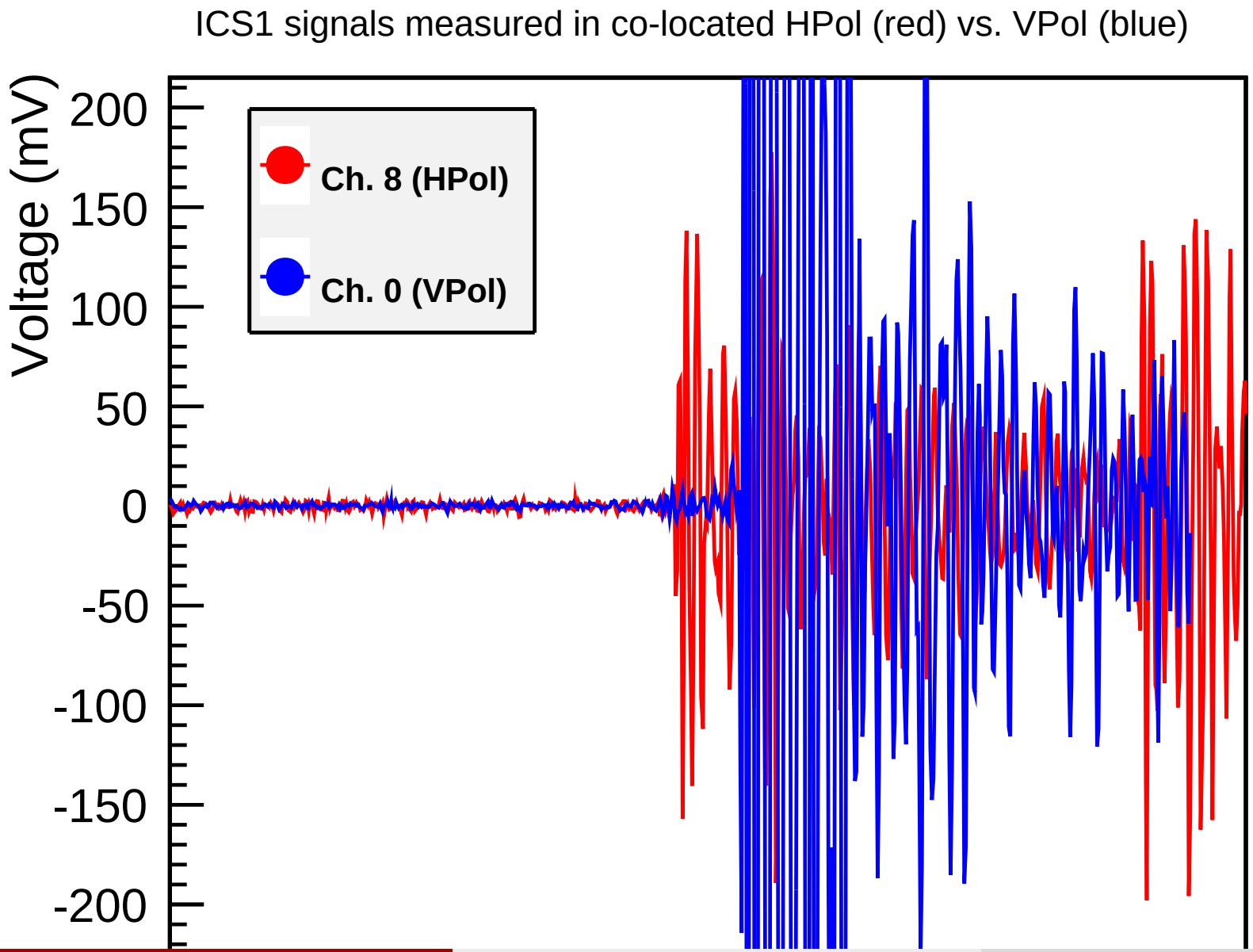
And BIREFRINGENCE! v depends on polarization



Inside the ice, only two stresses



BIREFRINGENCE! velocity depends on polarization



Making holes in the ice

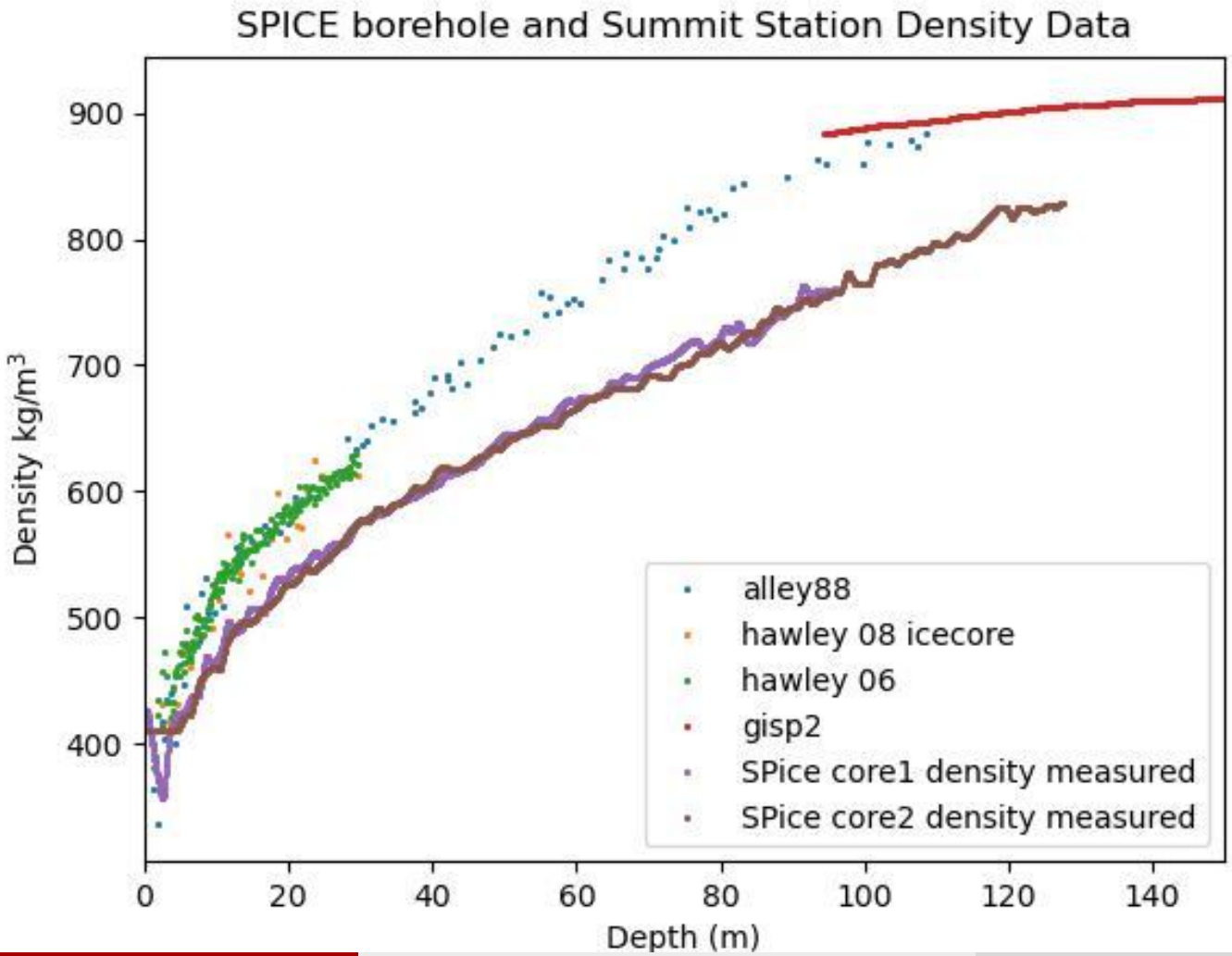
A hole

Summary of ice dielectric properties

- Ice attenuation length: 1000 m @ λ=1 m; 100 m @ λ=500 nm
- Ice scattering length: (TBD @ 1 m); 50 m @ λ=500 nm
- Ice index-of-refraction: n=1.78 @ λ=1 m; n=1.45 @ λ=500 nm
- Birefringence: δn/n$\sim$0.002 both radio/optical

Measuring ICE ϵ: 1. n(z)$\propto \rho$(z)?

Determines double pulse structure and extent of 'shadow zone'



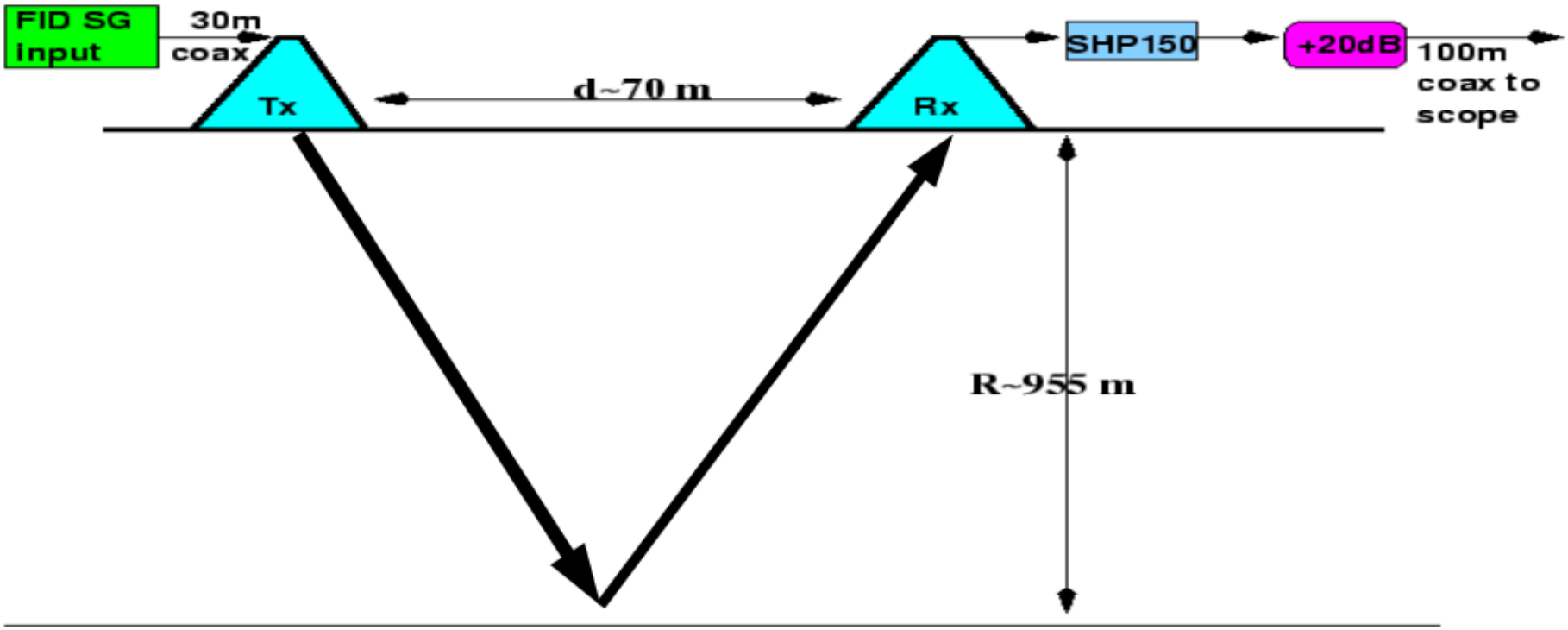
Volume Scattering? https://arxiv.org/pdf/2405.19472

What happens when radio waves interact with electrons in ice molecules?

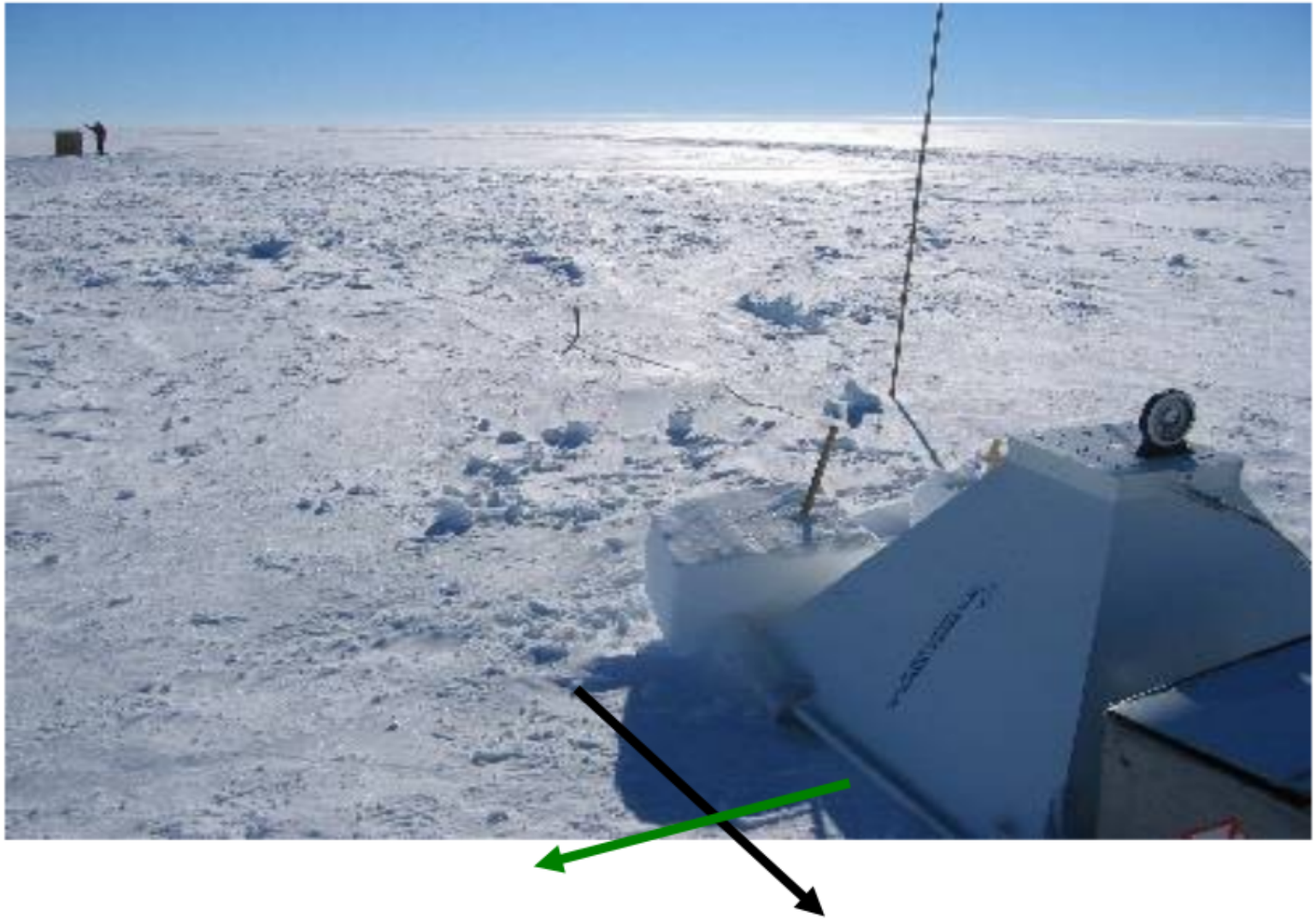
1. Coherent layer scattering: $P \propto 1/r^2$
2. Coherent/Incoherent volume scattering $P \propto 1/r^4$

Volume Scattering may add background to neutrino signals

Bistatic radar: Xray-ing the ice



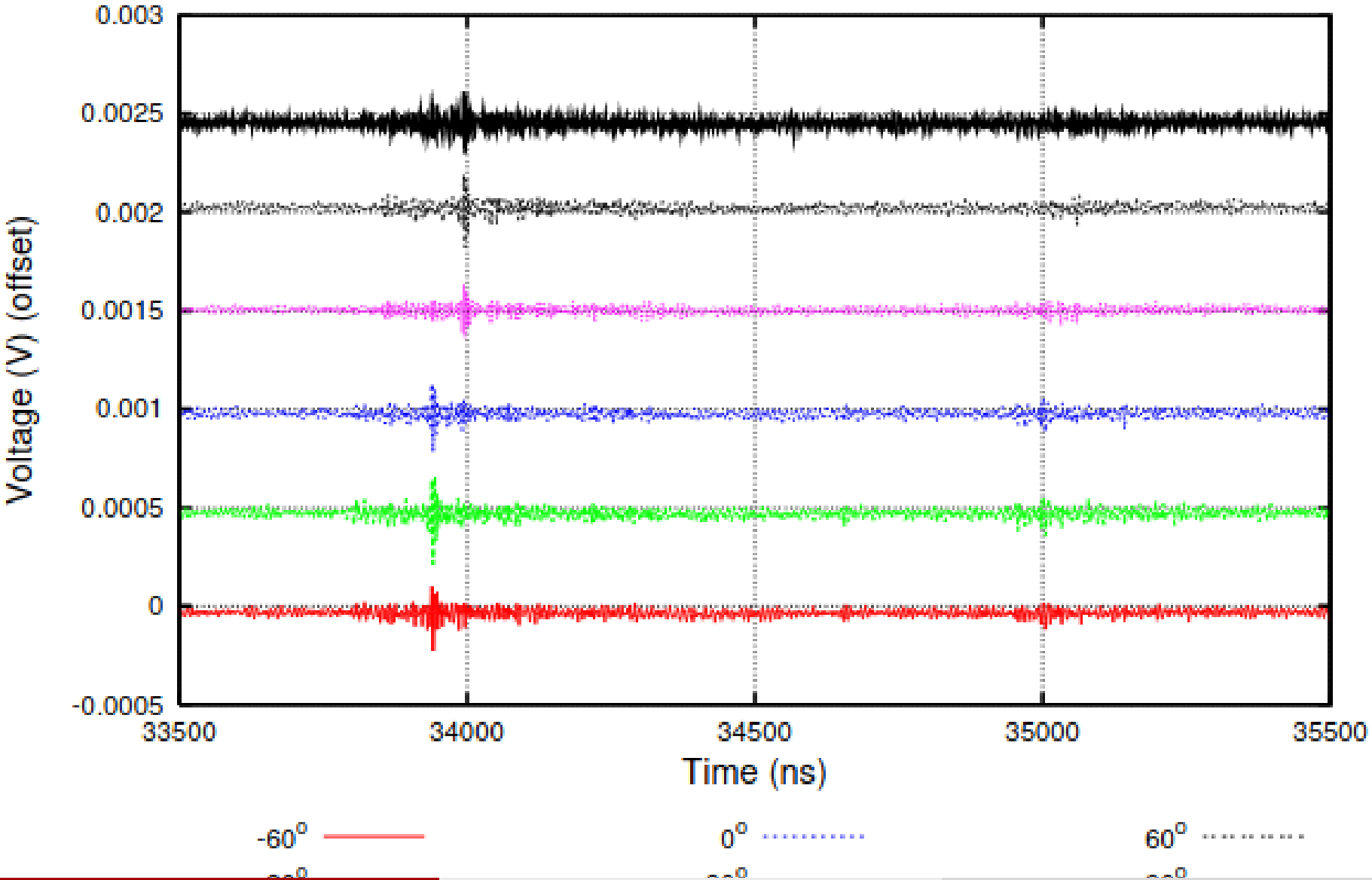
at Taylor Dome, Antarctica



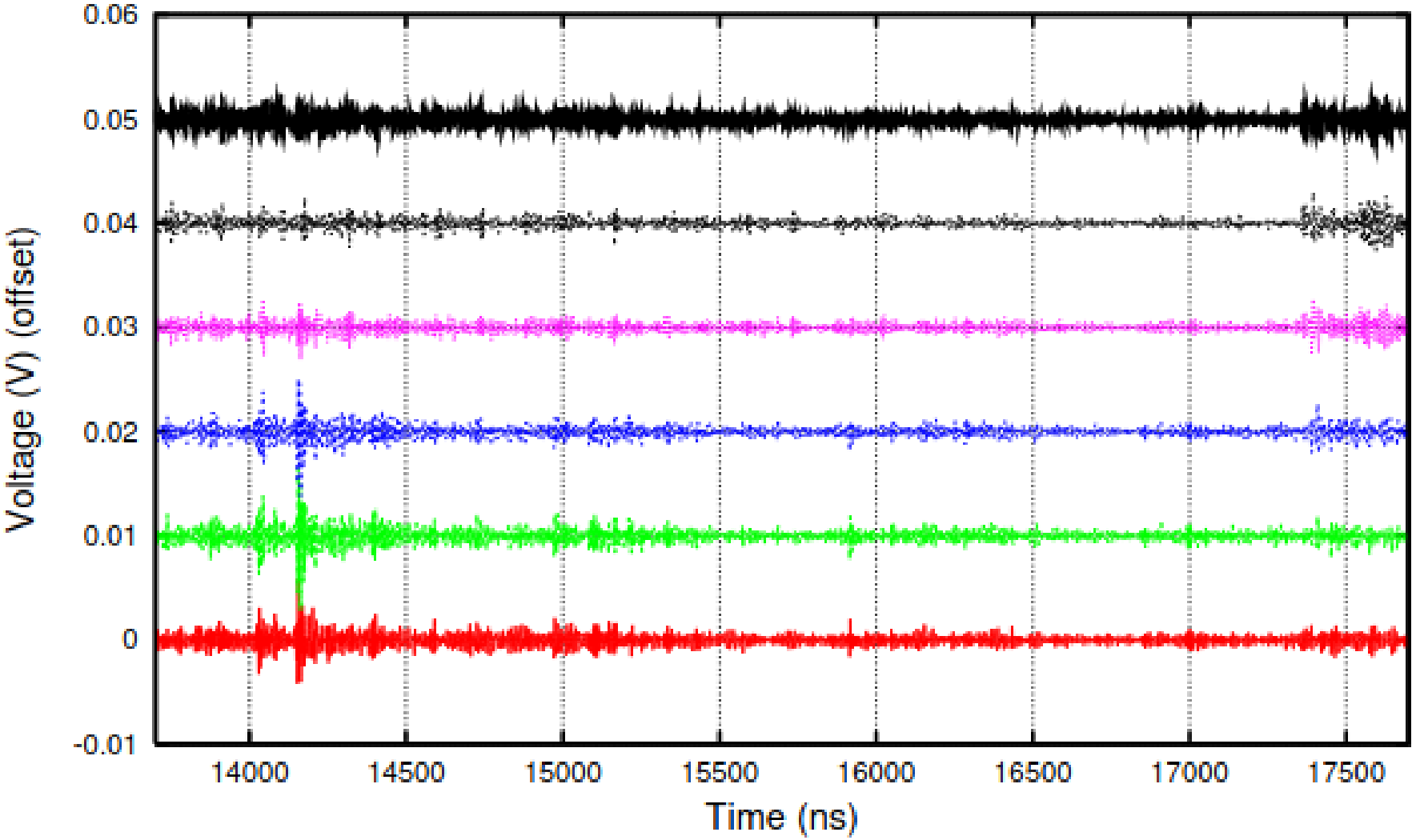
Bottom Reflection Studies.

Horn antennas send waves polarized along two perpendicular axes

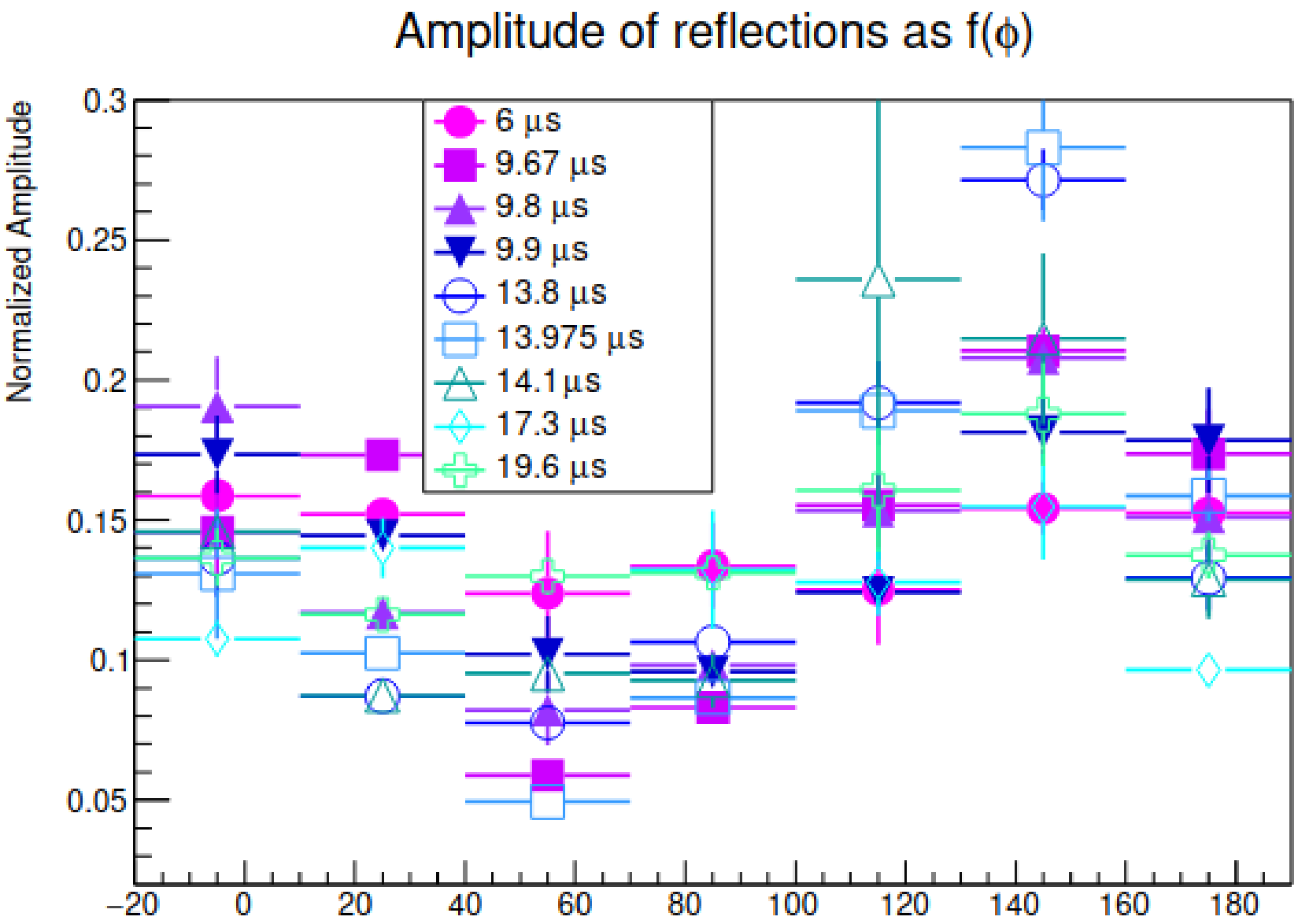
SP bedrock echo as f(ϕ)



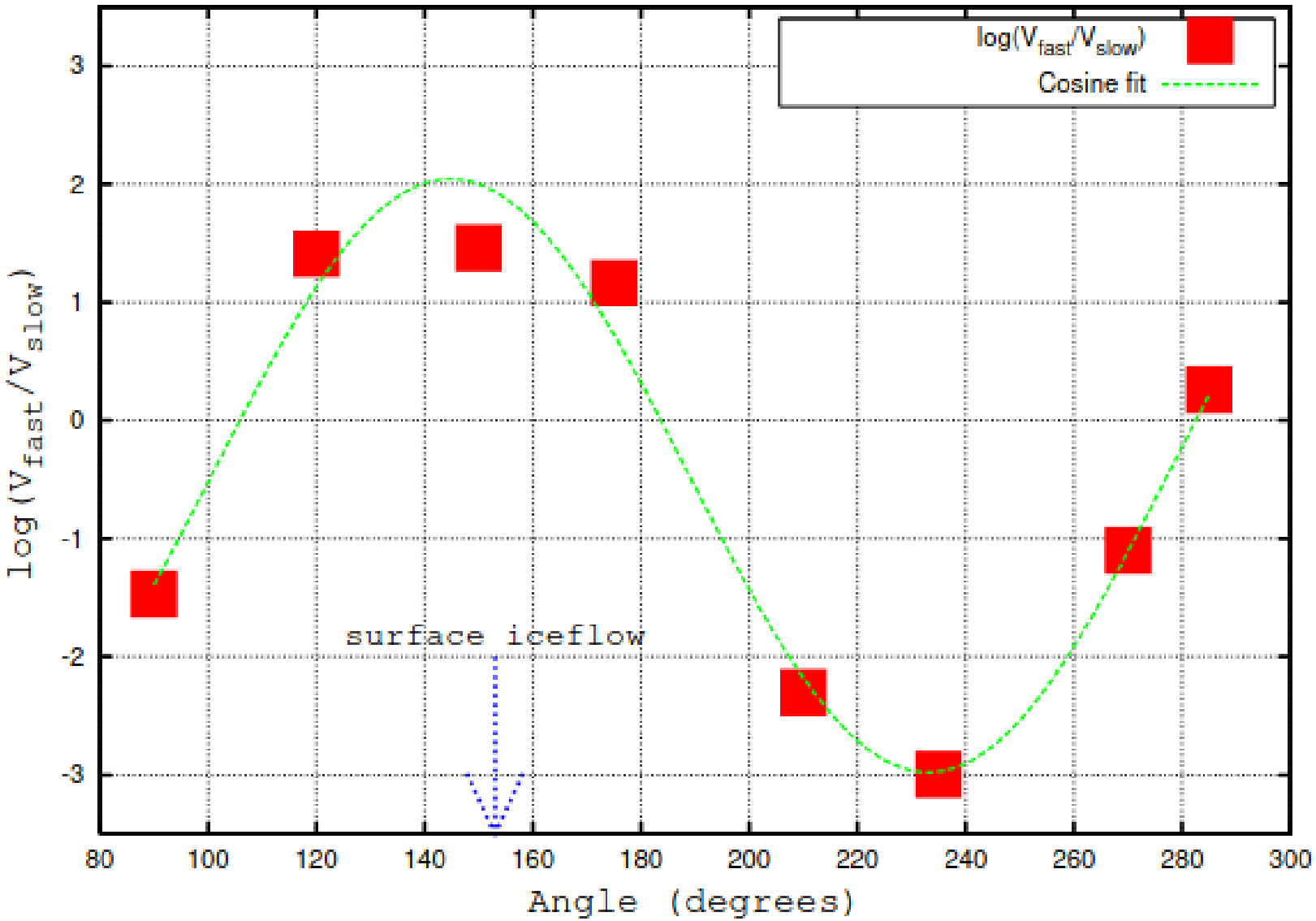
Internal layer echo as f(ϕ)



A(ϕ)

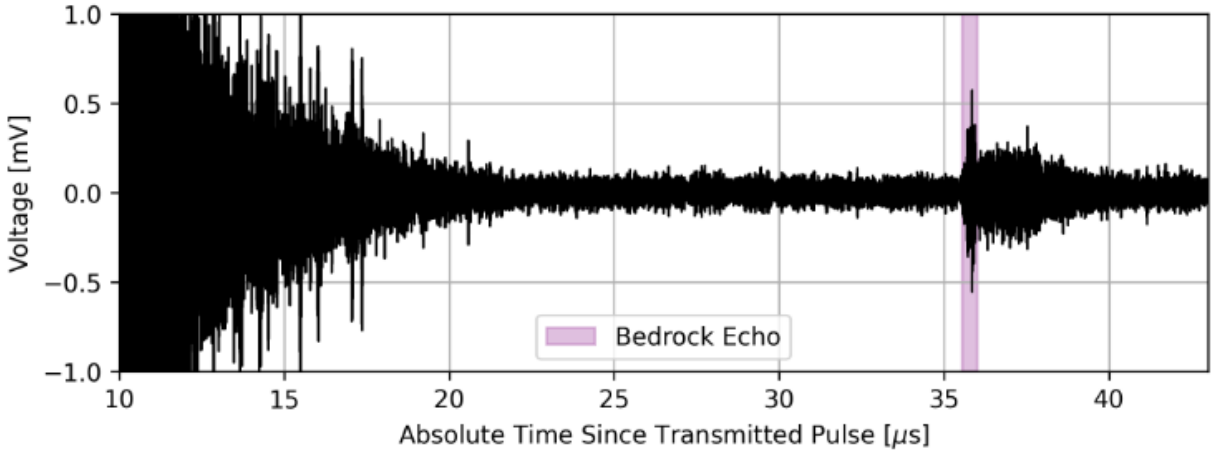

Amplitude of reflections as f(ϕ)
Normalized Amplitude
0.3
0.25
0.2
0.15
0.1
0.05
−20
0
20
40
60
80
100
120
140
160
180
6 µs
9.67 µs
9.8 µs
9.9 µs
13.8 µs
13.975 µs
14.1 µs
17.3 µs
19.6 µs

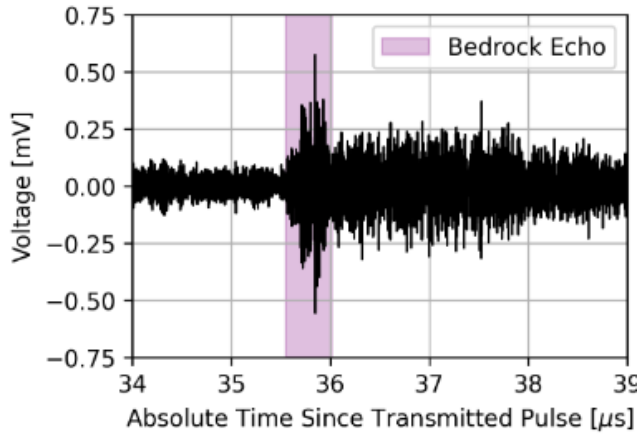
Bedrock echo strength as f(ϕ)

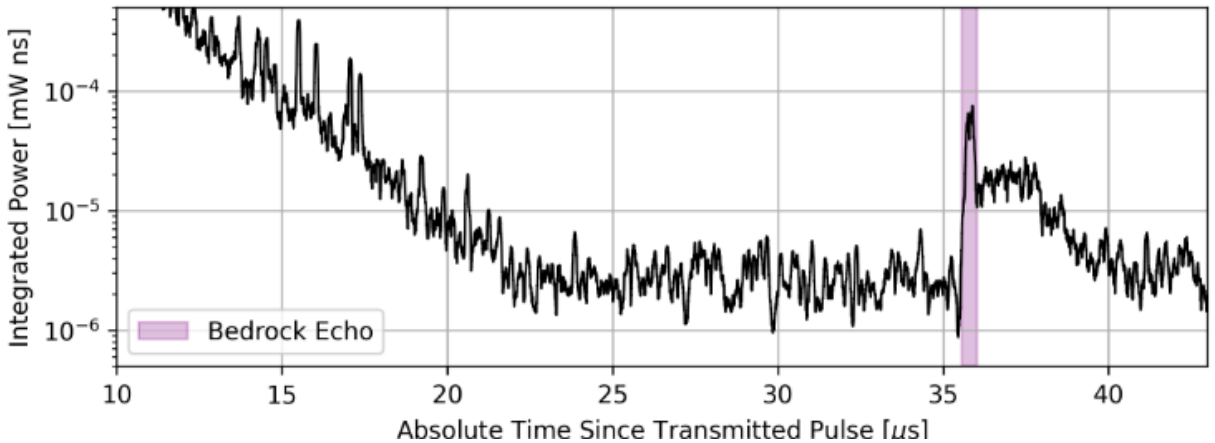


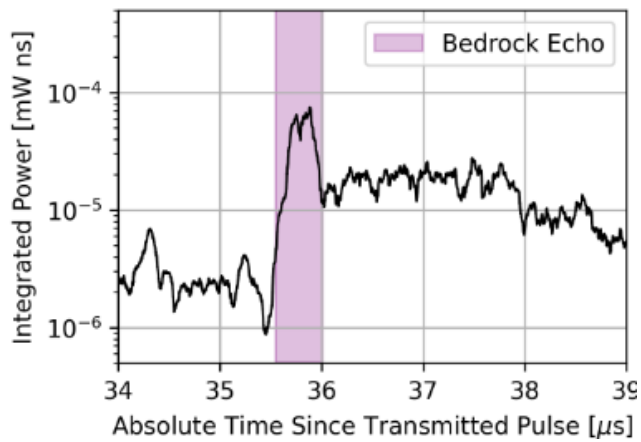
cf Summit Station echogram, August 2021

Note internal layers!

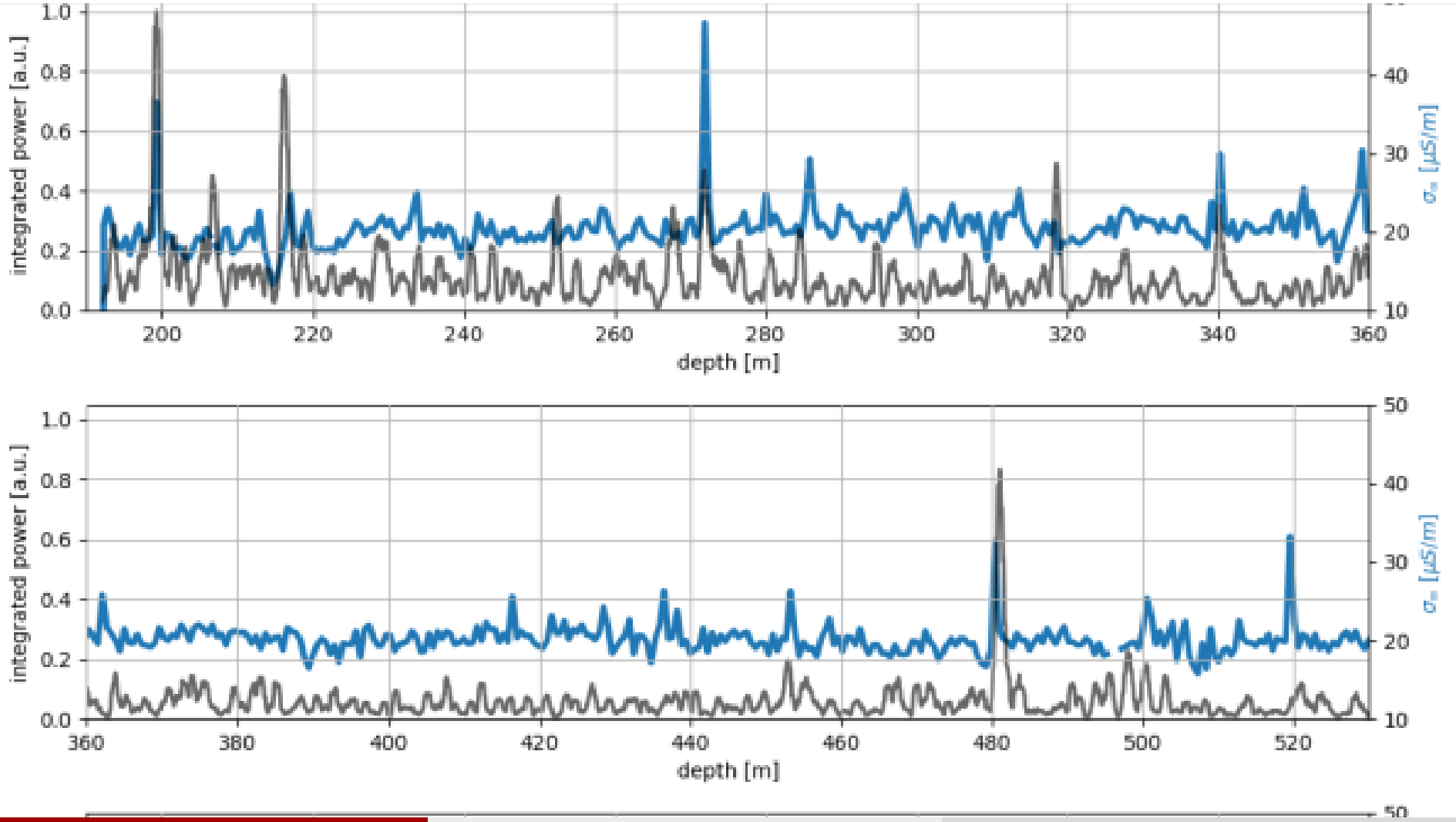


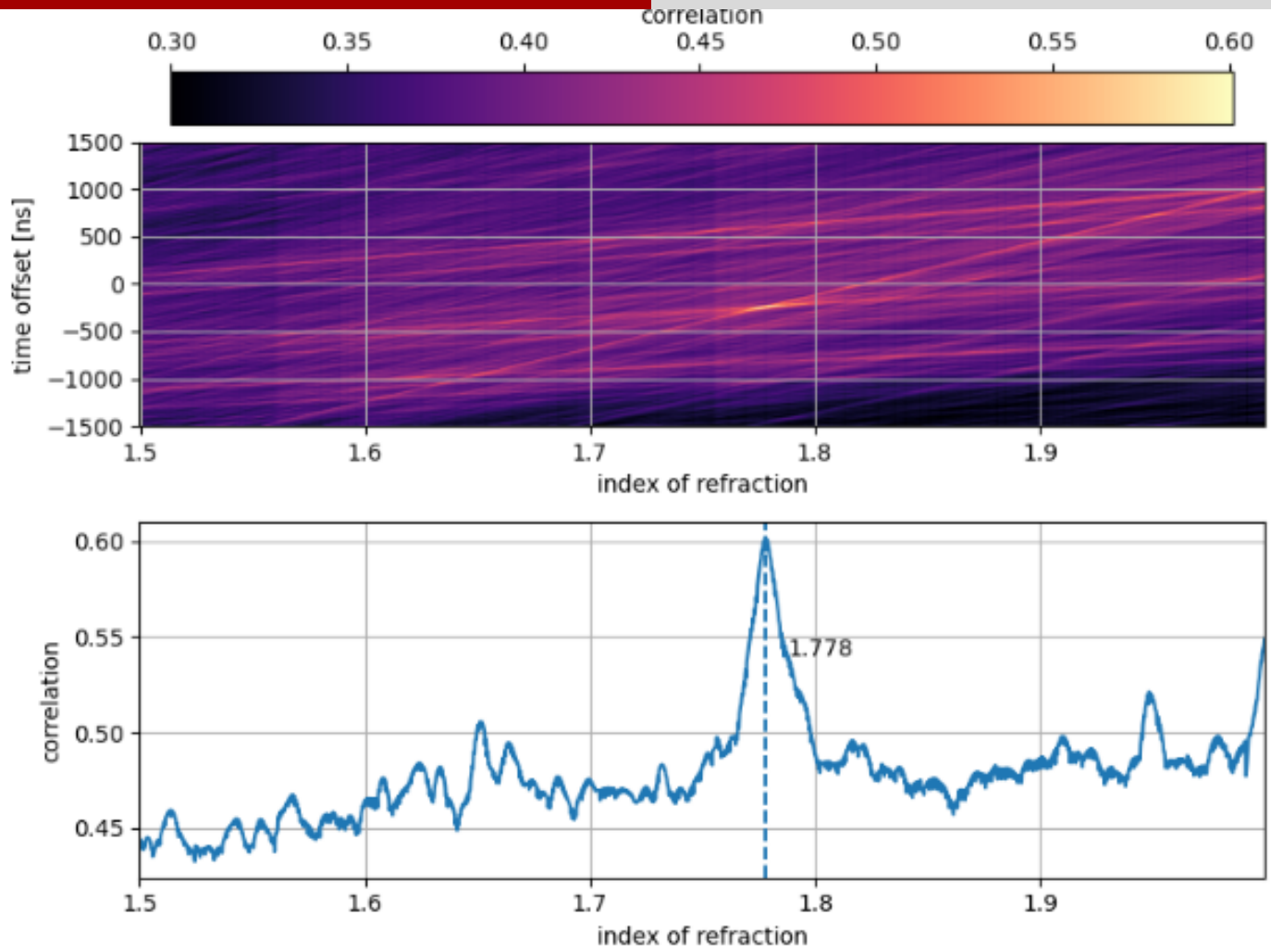




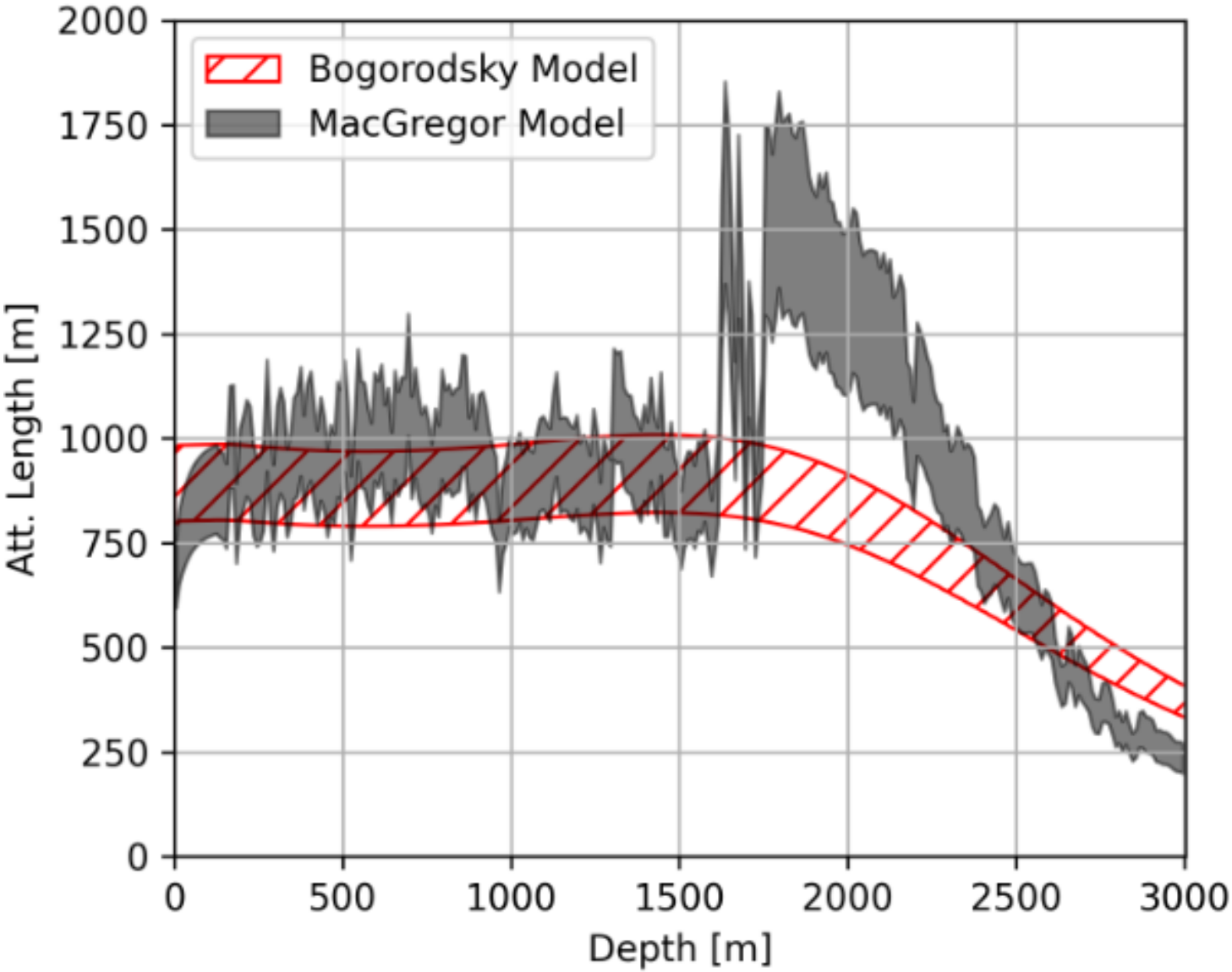


Stretch Radar echoes to layer conductivity




correlation
0.30
0.35
0.40
0.45
0.50
0.55
0.60
time offset [ns]
1500
1000
500
0
−500
−1000
−1500
1.5
1.6
1.7
1.8
1.9
index of refraction
correlation
0.60
0.55
0.50
0.45
1.778
1.5
1.6
1.7
1.8
1.9
index of refraction

Attenuation/Absorption Length

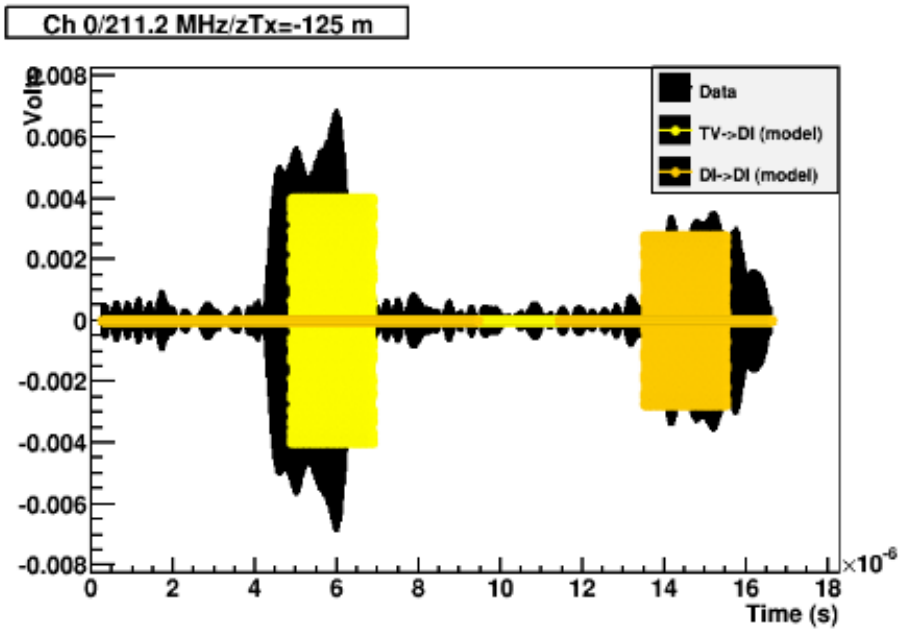


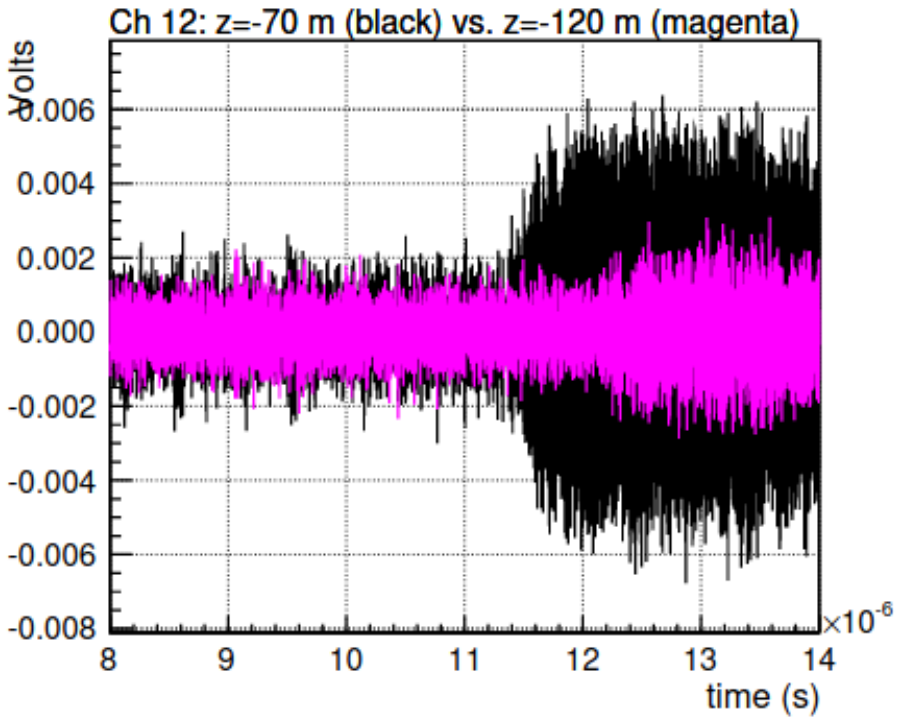
Greenland (RNO-G) vs. South Pole (ARA, ICG2R)

- Firn layer ($\propto$ shadowing) thickness ($n_{surface} \rightarrow n_{deep\ ice}$: 100 m/150 m)
- Attenuation Length, upper 1500 m: 1.5 km/0.9 km
- Attenuation Length, all depths: 0.65 km/0.8 km
- Birefringence: 0.002/$<$0.0002 (Summit!)
- ice thickness: 2.85 km/3.1 km

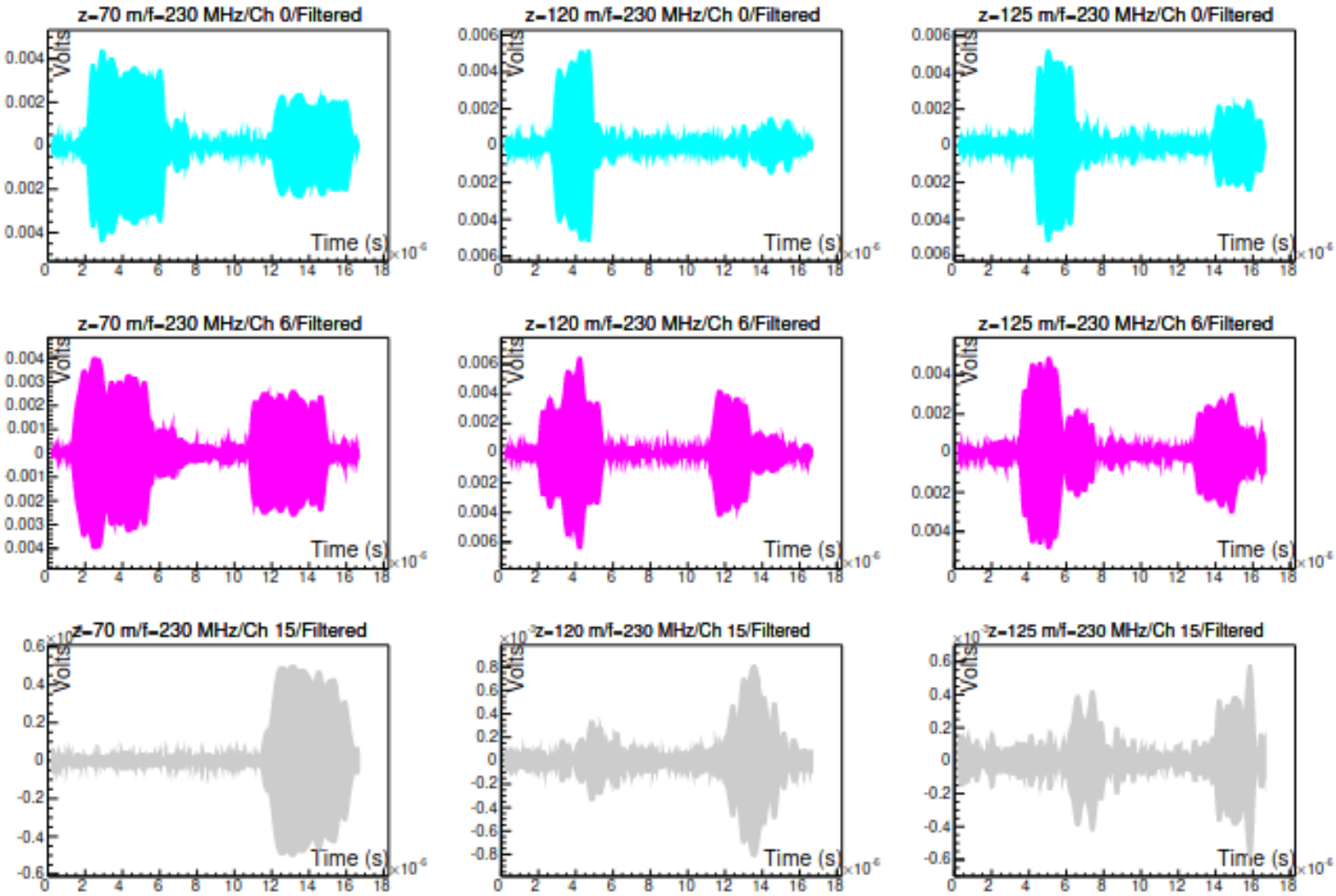
Shadow zone is unshadowed!

Signals traveling horizontally over 3 km

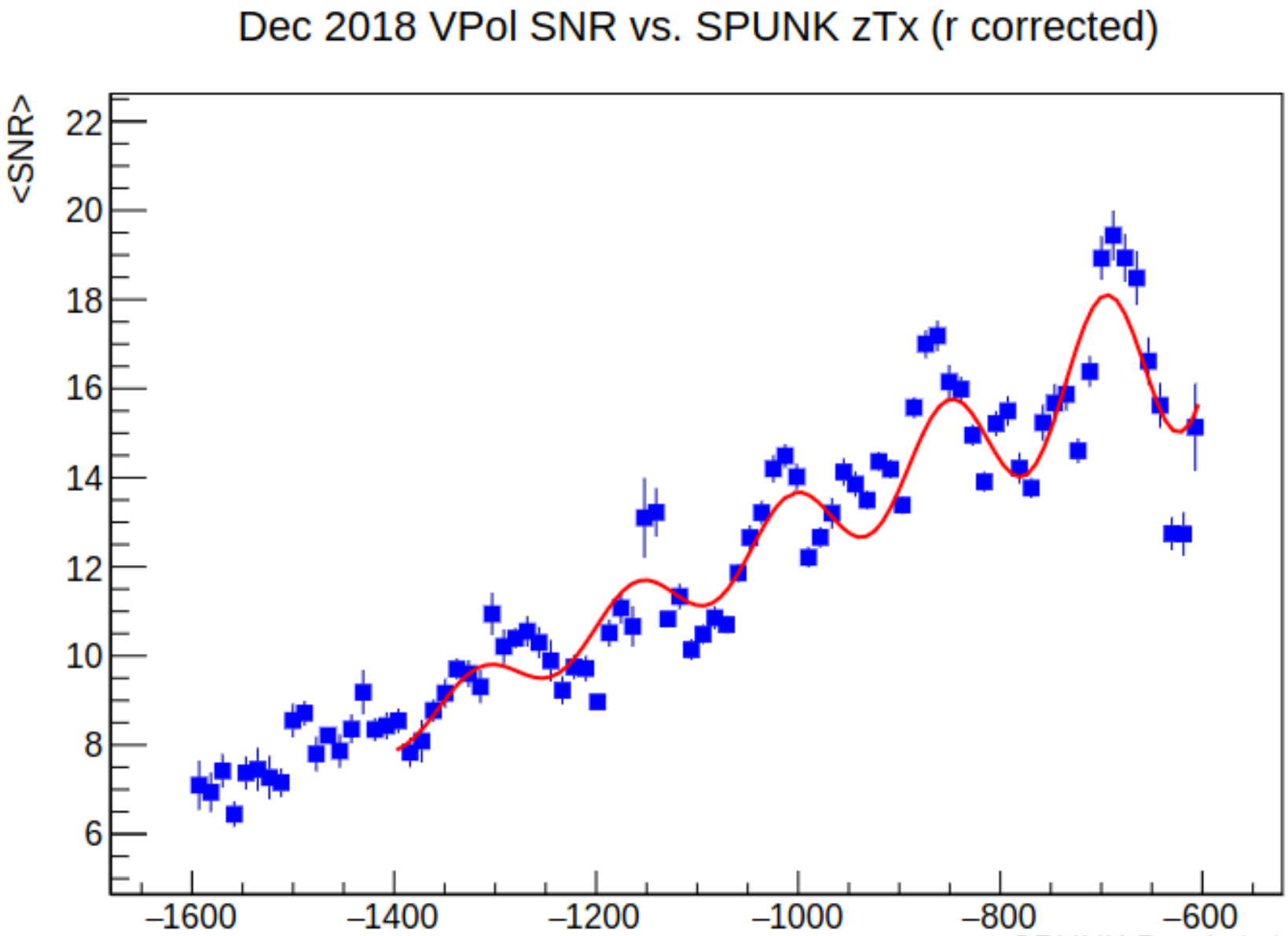




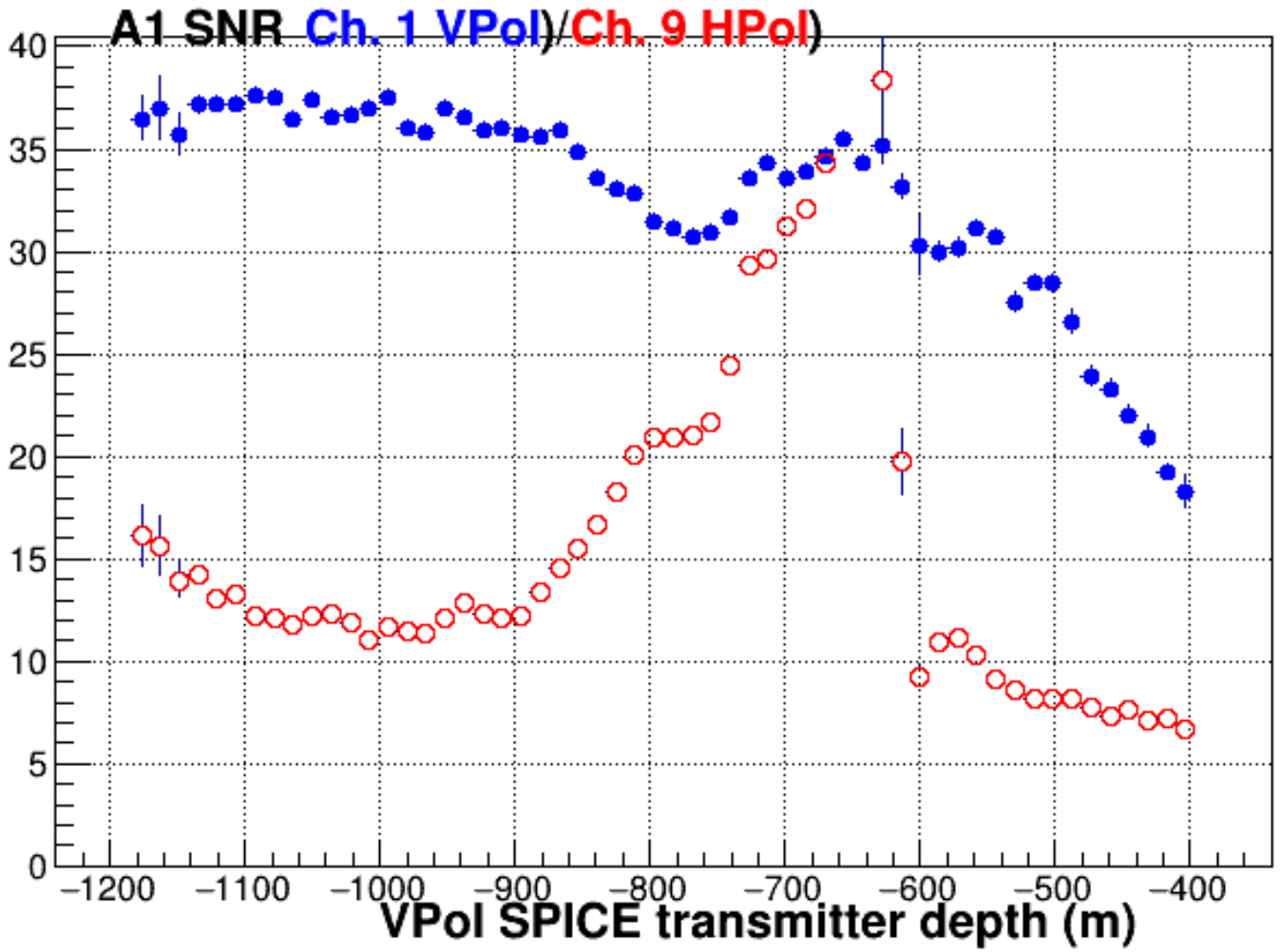
Shadow zone signals vary rapidly with depth and frequency!



Mysteries: Amplitude(depth)

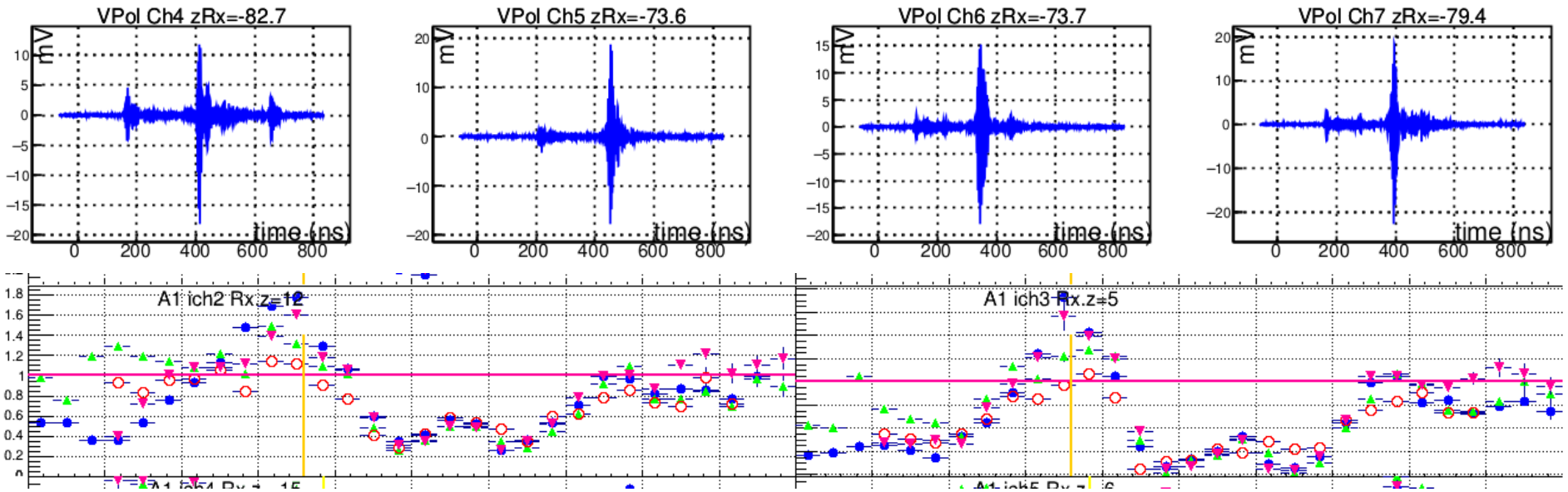


Mysteries: Amplitude(polarization,depth)



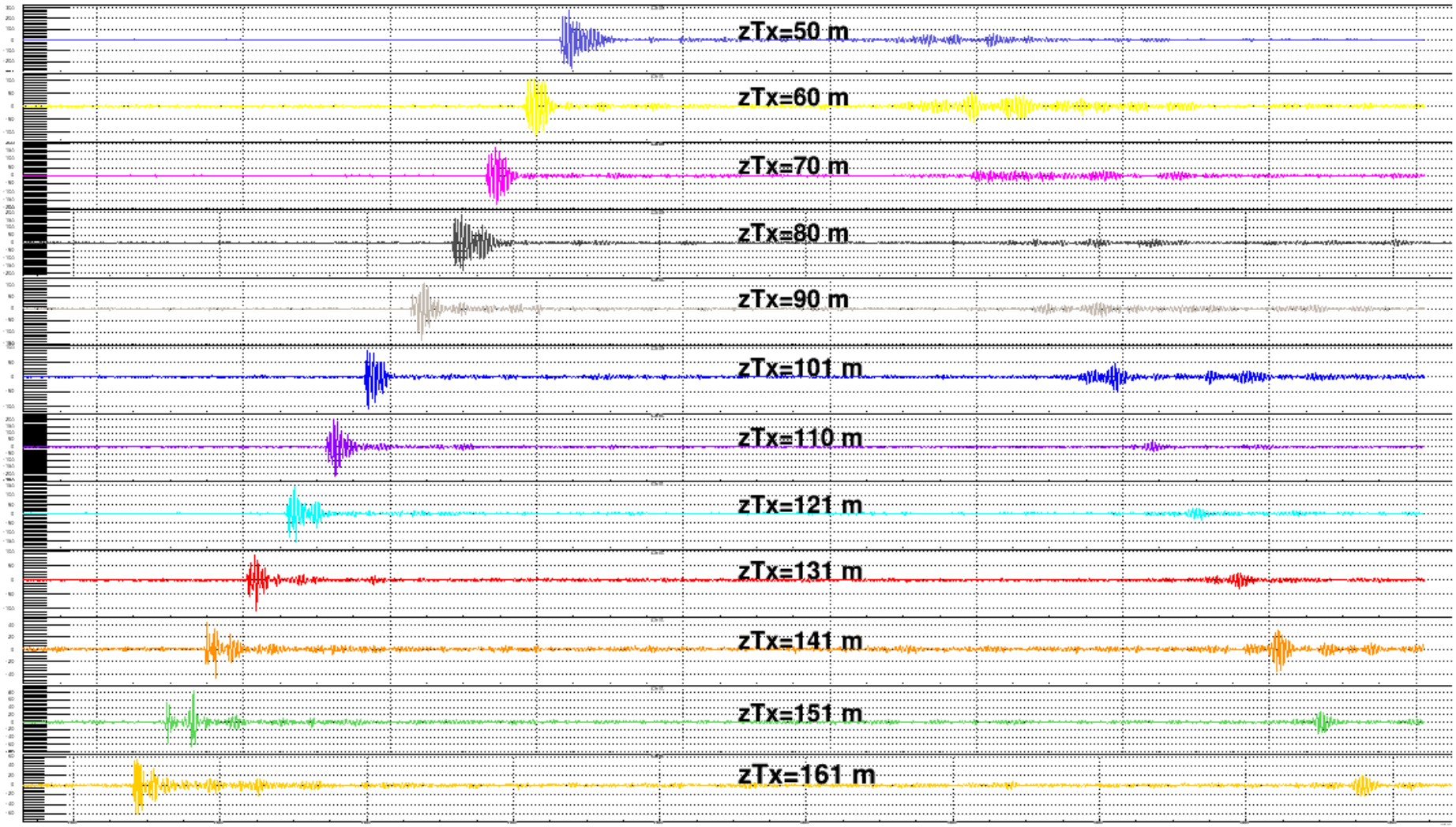
also cross-polarized power on reflection?

Why is the R signal so much stronger than D, particularly at the Refract→Reflect transition (where there should be a DROP in R signal, since some is now escaping!)



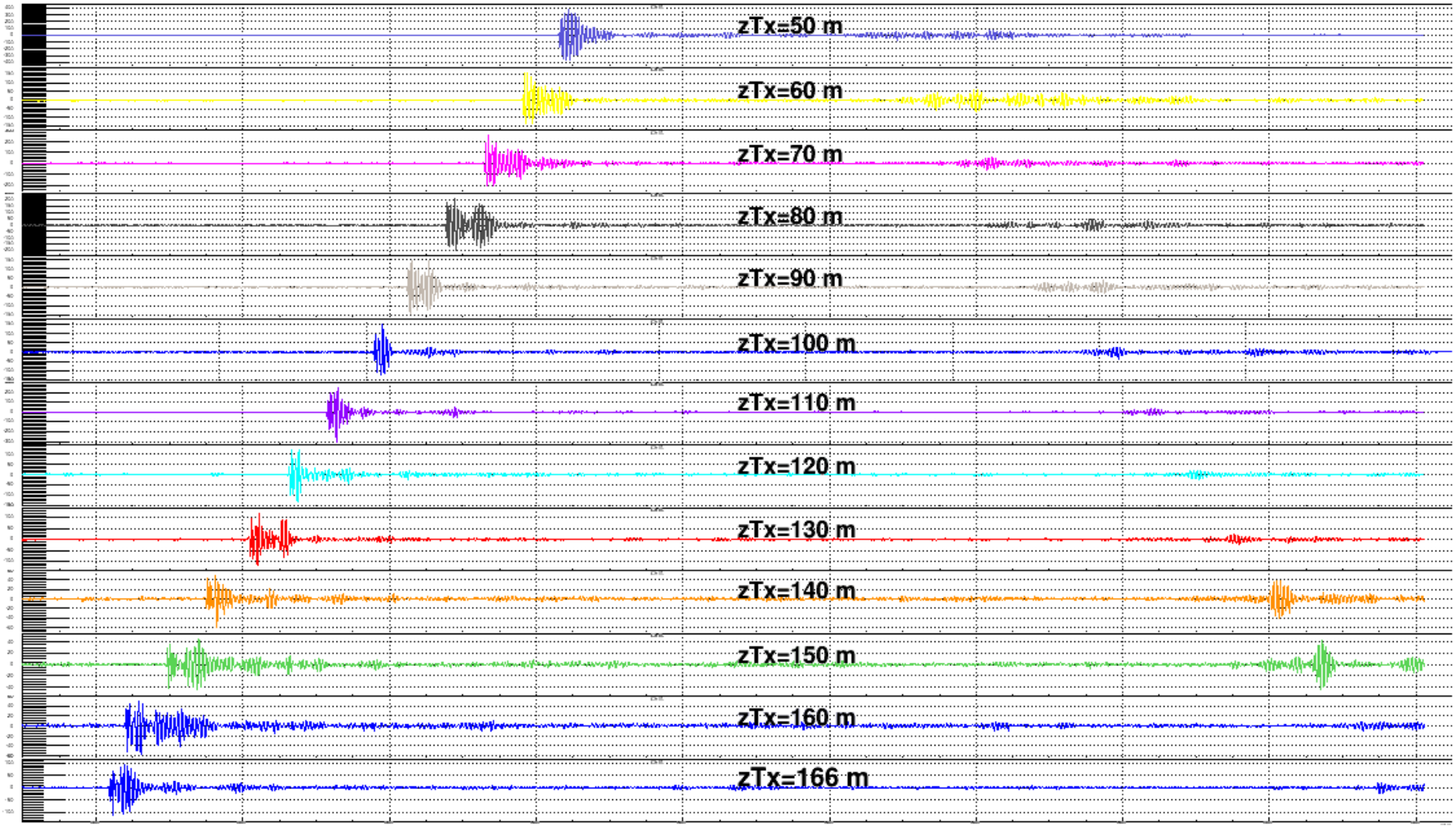
RICE B2xB4 - Tx↓

Note features on surface reflection!

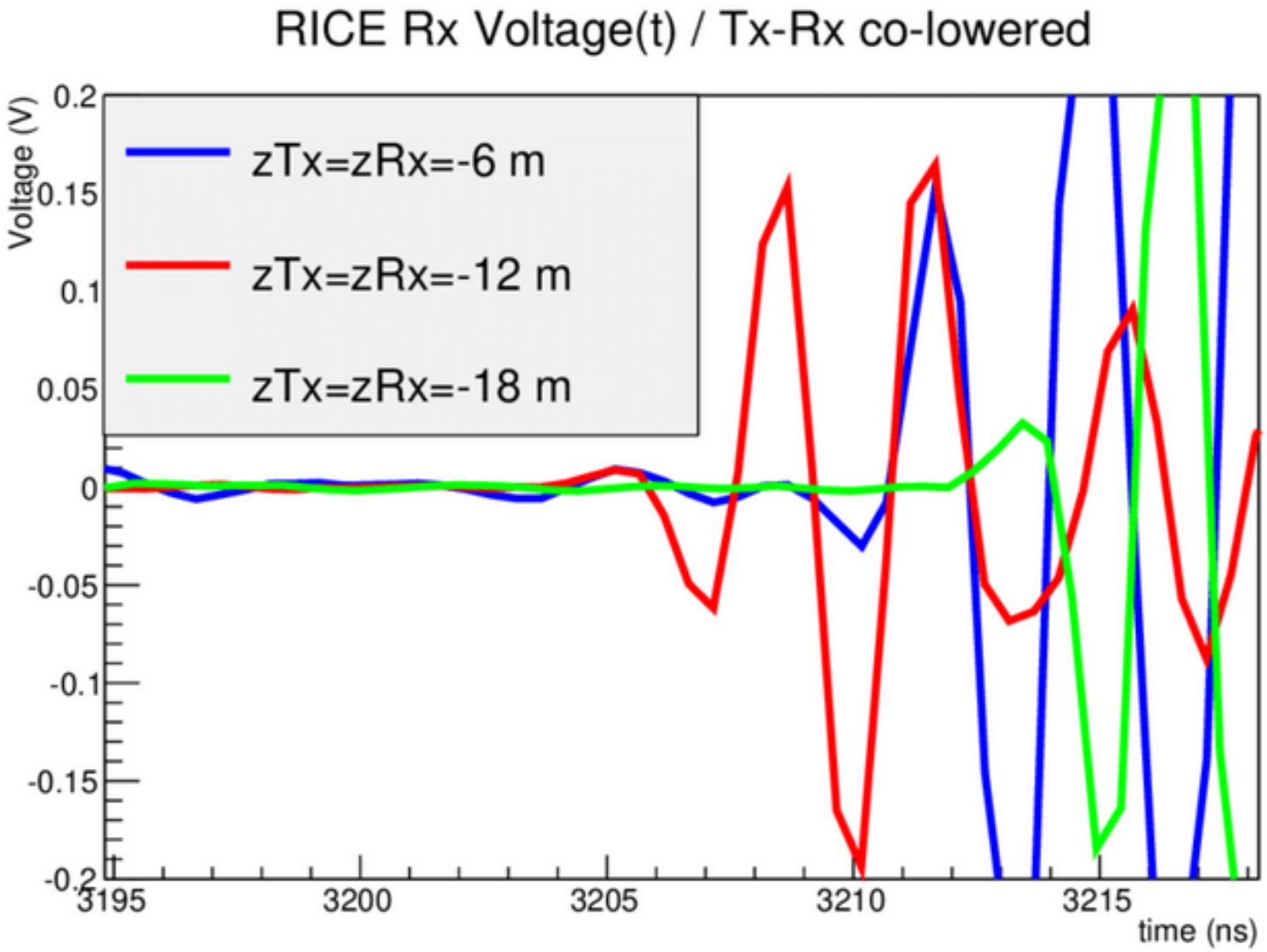


RICE B2xB4 - Tx↑

Reproducible!



Inversion in timing?



My summary

1. Radio wave measurements offers a path towards detection of ultra-high energy neutrinos
2. However, a) we've never detected one, and b) radio wave propagation through the ice have many more complexities than current simulations and estimates include
3. If we had a more complete fundamental understanding of all the impurities and anisotropies in the ice, we might be able to explain all this, but we are (many) years away from that!